Exploring the Unknown [In The "Intensity Frontier"]

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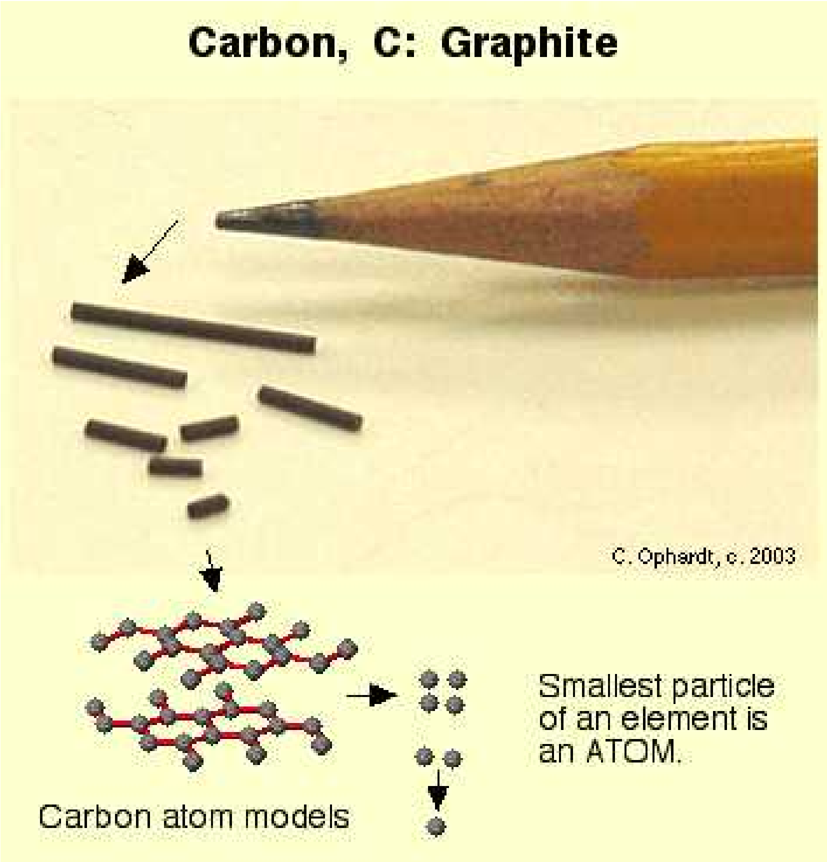
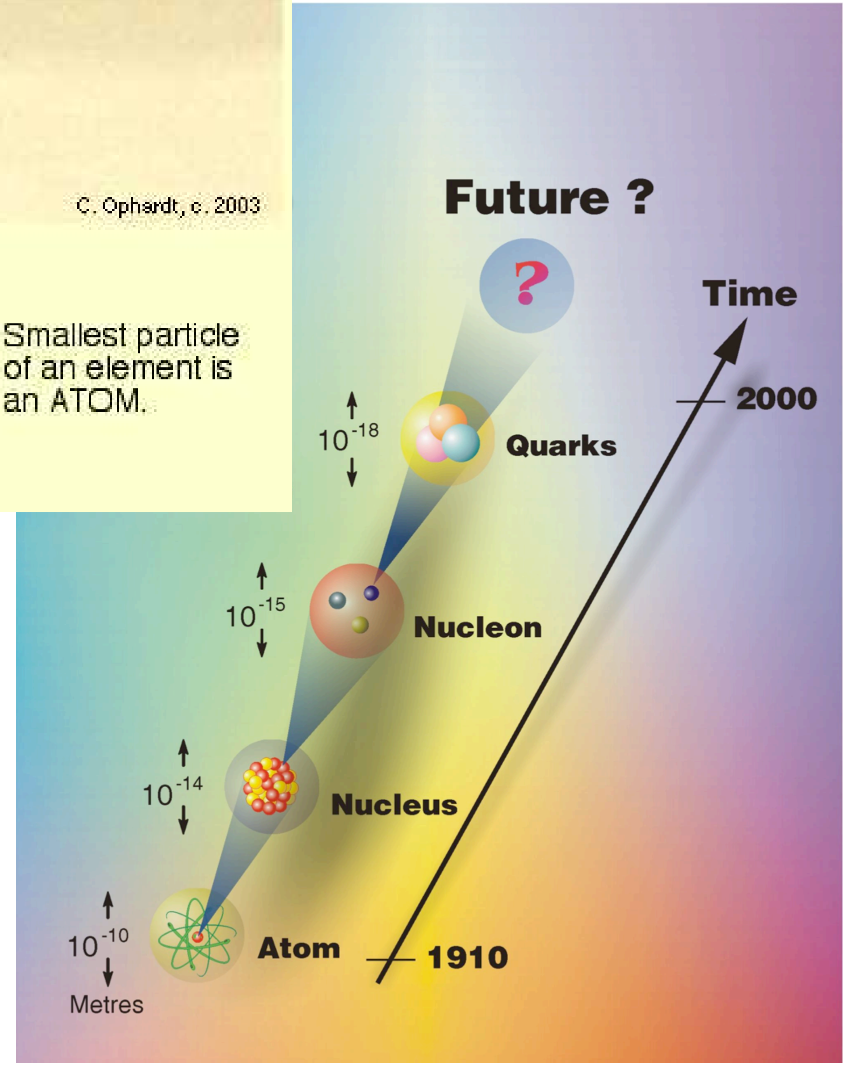
Undergraduate Lecture Series – Fermilab

June 25, 2015



- What are basic ingredients of matter?
- How do they interact with one another?



Particle Physics

Questions:

- What are the most fundamental laws that describe all natural phenomena (at least in principle)?
- And several more pragmatic question:
  - how do stars shine?
  - heavy elements?
  - ...

Periodic Table of Elements

Atomic # / Symbol / Name / Atomic Mass

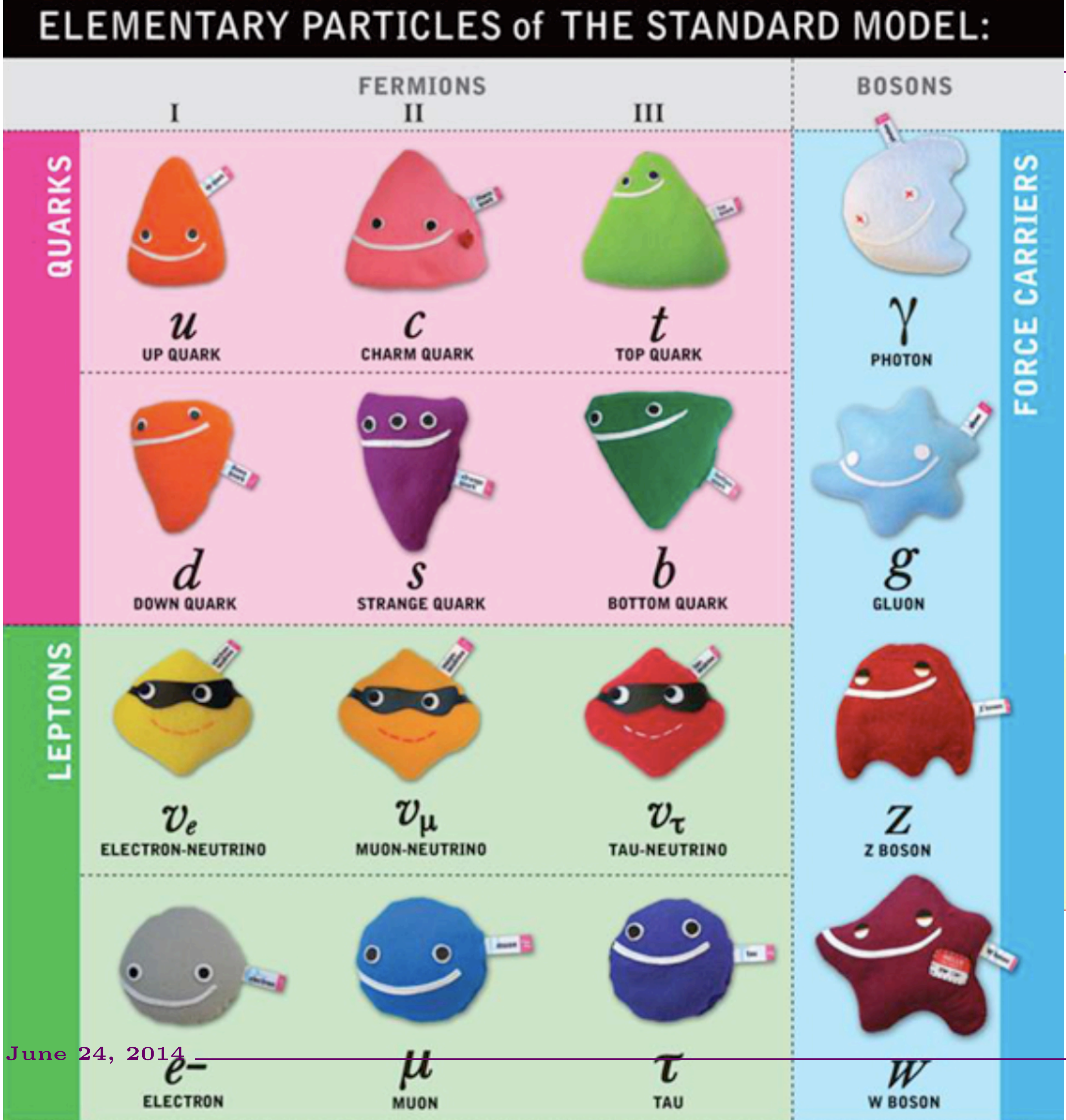
C Solid · Hg Liquid · H Gas · Rf Unknown

Metals: Alkali metals · Alkaline earth metals · Lanthanoids · Actinoids · Transition metals · Poor metals
Nonmetals: Other nonmetals · Noble gases

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen 1.00794																	2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)



21st Century Periodic Table

(Now with Higgs boson!)

http://www.particlezoo.net

Evidence for Physics Beyond the Standard Model

1. The expansion rate of the universe seems to accelerate, both early on (inflation) and right now (dark energy).
2. Dark matter seems to exist.
3. Why is there so much baryonic matter in the universe?
4. Neutrino masses are not zero.

1. and 2. are consequences of astrophysical/cosmological observations. It is fair to ask whether we are sure they have anything to do with particle physics.

3. is also related to our understanding of the early history of the universe and requires some more explaining.

4. is the only palpable evidence for new physics.

Very different techniques are used in order to pursue fundamental particle physics questions. We combine those into three **Frontiers**: the Energy Frontier, the Cosmic Frontier, and – the I am going to concentrate on – the Intensity Frontier.

"The Intensity Frontier consists of research efforts where one aims at probing nature through precision studies of the properties and fundamental interactions of its basic constituents. While many of these efforts – especially the ones pertinent to Fermilab – revolve around particle accelerators, the energy of the accelerator is not 'as high as possible' but is rather dictated by the physics question one is interested in addressing. Instead, it is the intensity and "quality" (purity, time and space profile, etc) of the accelerated beam, that determine the reach of intensity frontier experiments. Past, current, and future Intensity Frontier experiments include studies of neutrino oscillations, searches for rare muon, pion, and kaon processes, precision measurements of muon properties, heavy flavor (charm and bottom) factories and the LEP1 experiments (the energy was fixed at a special value, the Z-pole mass)."

[AdG, N. Saoulidou, Ann. Rev. Nucl. Part. Sci. 60, 513-538 (2010).]

Cosmic Frontier

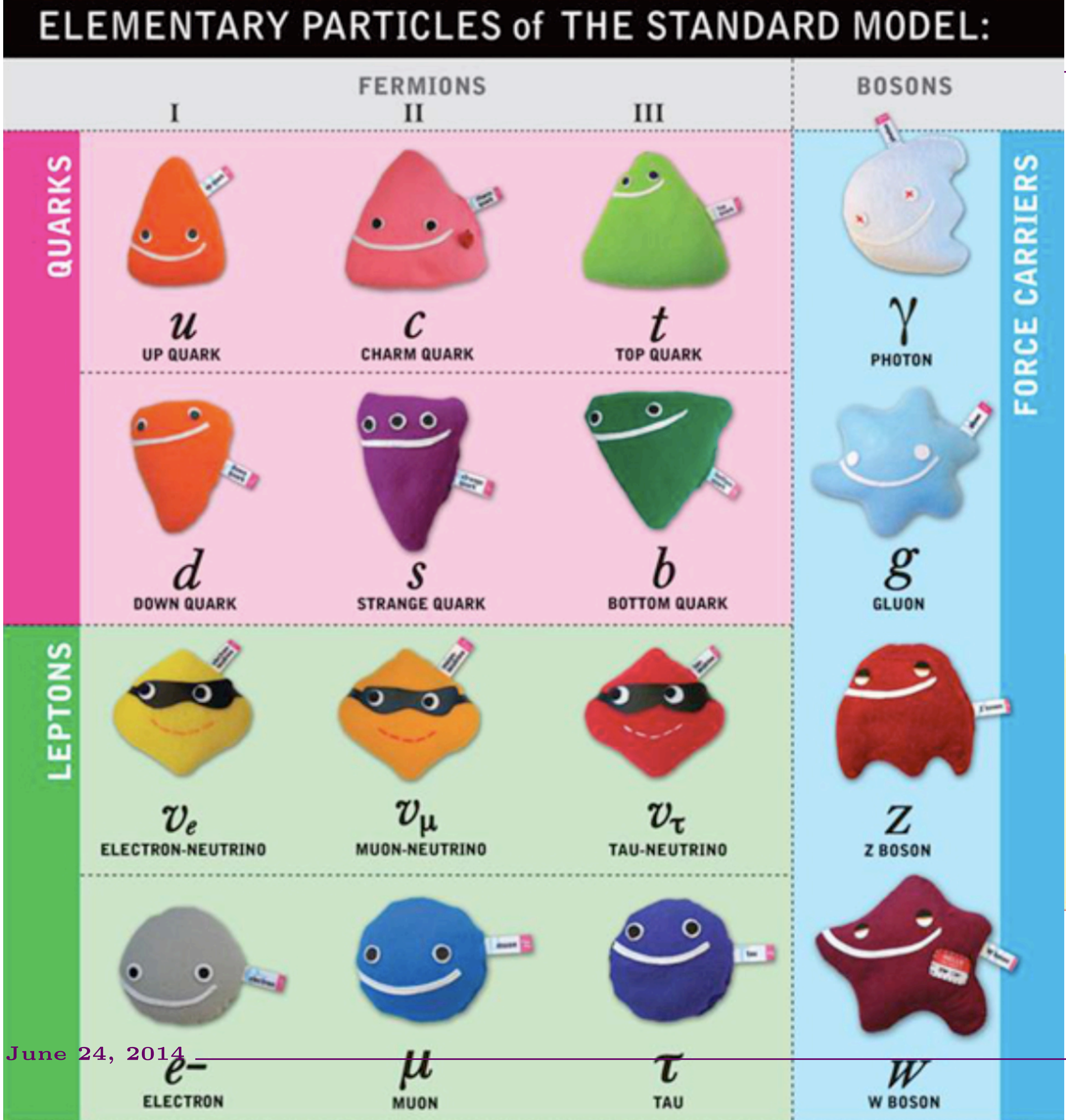
(What is most of the matter
in the universe?)

Intensity Frontier

(Where do neutrino masses come from?)

Energy Frontier

(Understand the Higgs Boson)



Intensity Frontier

Study the properties of the basic ingredients in as much detail as possible.

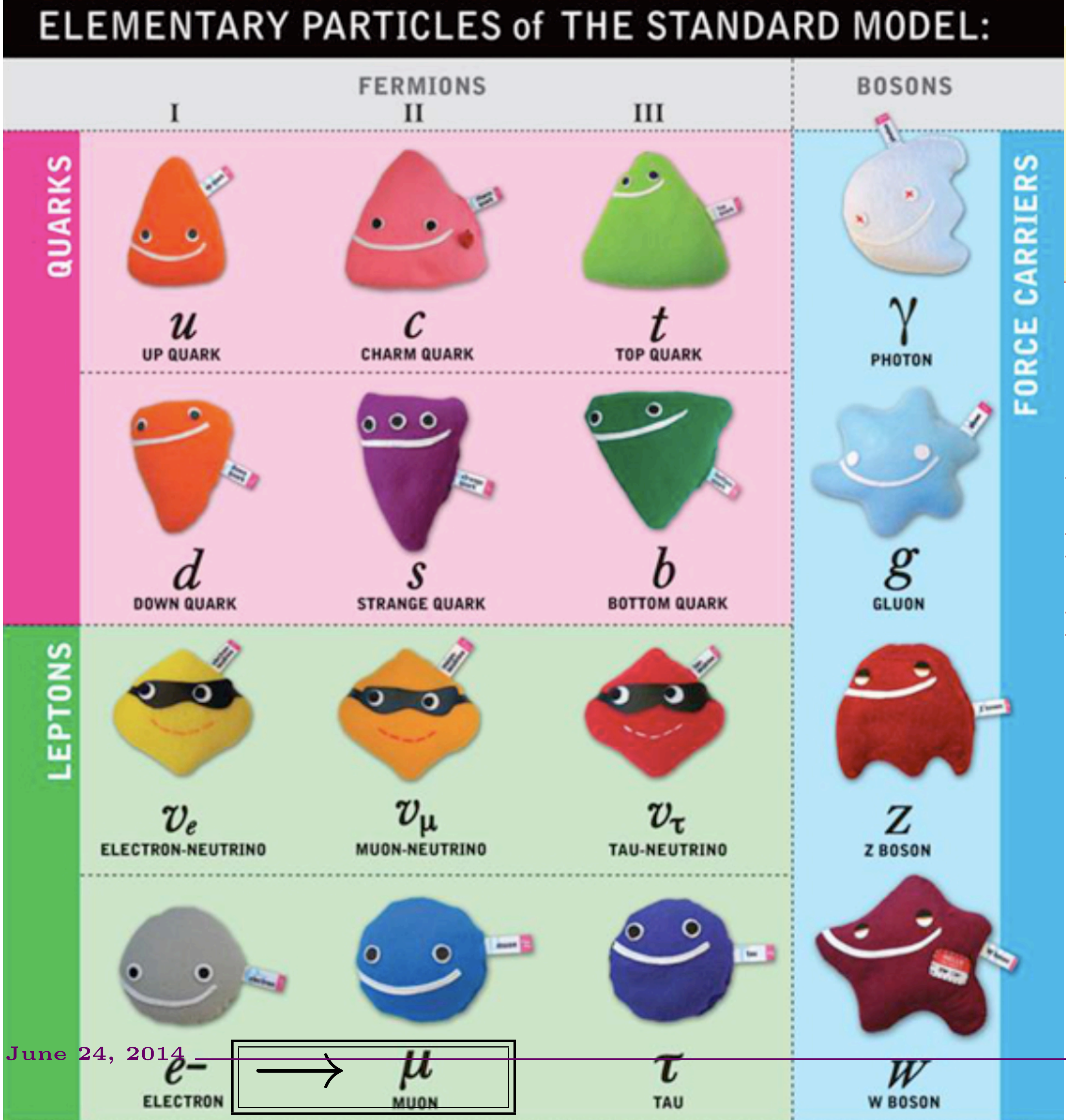
http://www.particlezoo.net

Intensity Frontier – In Practice

The idea is to either

- **Measure something very, very precisely**, and compare the result with theoretical computations. If the results disagree, there is some physics that has been left out.
- **Look for phenomena that are not supposed to happen**, or which are expected to be insanely rare.

Either way, you need **lots of particles**, and you need to make sure you understand your initial states really well.



The Muon is Among a Handful of Known Fundamental, Point-Like Particles.

$$\text{muon} = \mu$$

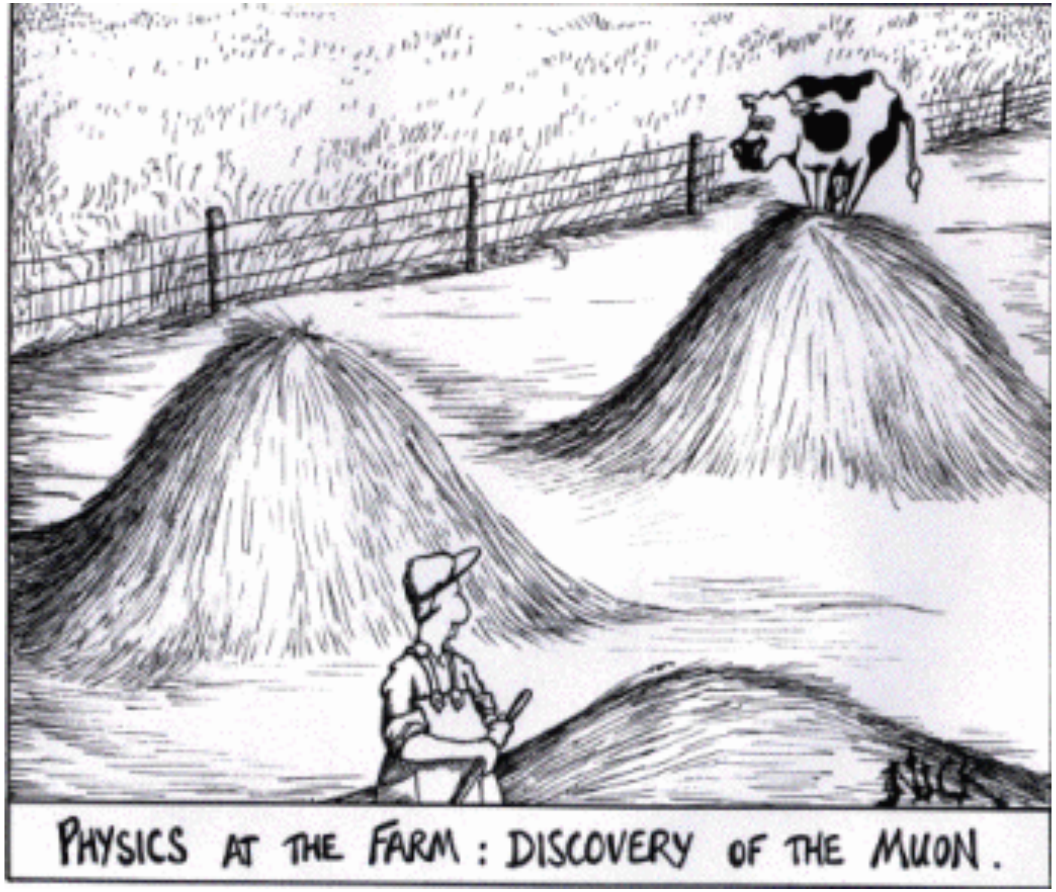
('mu')

http://www.particlezoo.net

Muons were discovered in 1936 in cosmic ray experiments.

Almost 100% of the time, they decay into an electron and two neutrinos,

$$\boxed{\mu^- \to e^- \bar{\nu}_e \nu_\mu}$$



(It's kind of a funny story.)

“Who Ordered That?”

The muon is the best known unstable fundamental particle.

The muon is also the heaviest fundamental particle we can directly work with. It is a unique, priceless resource for physicists.

Citation: W.-M. Yao et al. (Particle Data Group), J. Phys. G 33, 1 (2006) (URL: http://pdg.lbl.gov)

μ $J = \frac{1}{2}$

μ MASS (atomic mass units u)

The primary determination of a muon's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the muon in u. In this datablock we give the result in u, and in the following datablock in MeV.

VALUE (u)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.113428926 4±0.0000000030	MOHR	05	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.1134289168±0.0000000034	[1] MOHR	99	RVUE	1998 CODATA value
0.113428913 ±0.00000017	[2] COHEN	87	RVUE	1986 CODATA value

[1] MOHR 99 make use of other 1998 CODATA entries below.
[2] COHEN 87 make use of other 1986 CODATA entries below.

μ MASS

2002 CODATA gives the conversion factor from u (atomic mass units, see the above datablock) as 931.494 043 (80). Earlier values use the then-current conversion factor. The conversion error dominates the masses given below.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
105.6583692±0.0000094	MOHR	05	RVUE		2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.6583568±0.0000052	MOHR	99	RVUE		1998 CODATA va
105.658353 ±0.000016	[3] COHEN	87	RVUE		1986 CODATA va
105.658386 ±0.000044	[4] MARIAM	82	CNTR	+	
105.65836 ±0.00026	[5] CROWE	72	CNTR		
105.65865 ±0.00044	[6] CRANE	71	CNTR		

[3] Converted to MeV using the 1998 CODATA value of the conversion const: 931.494013 ± 0.0000037 MeV/u.
[4] MARIAM 82 give $m_\mu/m_e = 206.768259(62)$.
[5] CROWE 72 give $m_\mu/m_e = 206.7682(5)$.
[6] CRANE 71 give $m_\mu/m_e = 206.76878(85)$.

μ MEAN LIFE τ

Measurements with an error > 0.001×10^{-6} s have been omitted.

VALUE (10^{-6} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

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The muon is also the heaviest fundamental particle we can directly work with. It is a unique, priceless resource for physicists.

ANS: "We did!"

μ MEAN LIFE τ

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The Muon Magnetic Dipole Moment

The magnetic moment of the muon is defined by $\vec{M} = g_\mu \frac{e}{2m_\mu}\vec{S}$.

The Dirac equation predicts $g_\mu = 2$, so that the anomalous magnetic moment is defined as (note: dimensionless)

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

In the standard model, the (by far) largest contribution to a_μ comes from the one-loop QED vertex diagram, first computed by Schwinger:

$$a_\mu^{QED}(1-\mathrm{loop}) = \frac{\alpha}{2\pi} = 116,140,973.5 \times 10^{-11}$$

The theoretical estimate has been improved significantly since then, mostly to keep up with the impressive experimental reach of measurements of the $g-2$ of the muon.

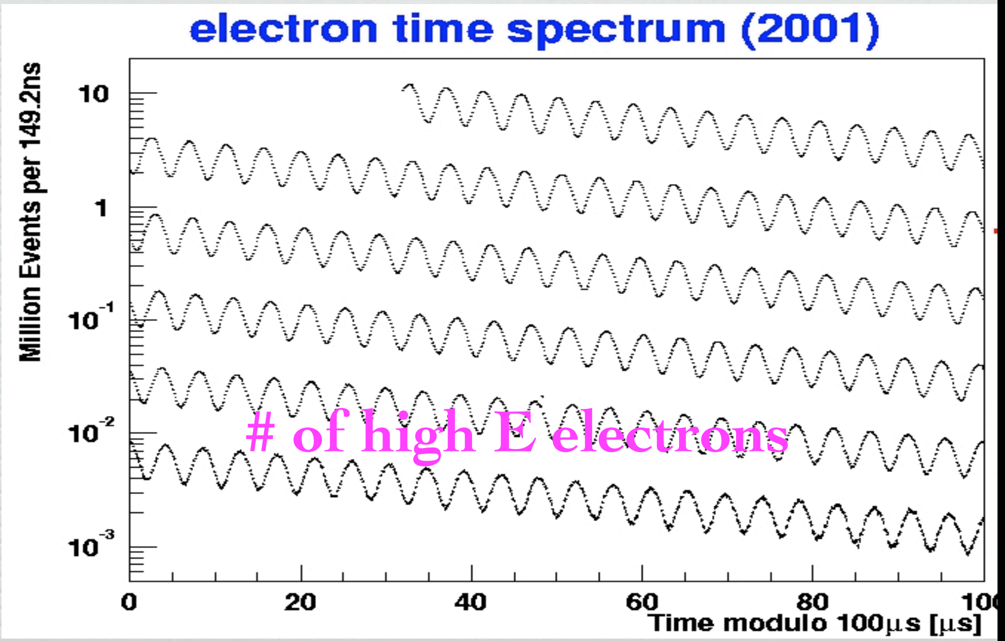
Spin Precession w.r.t. Momentum Vector

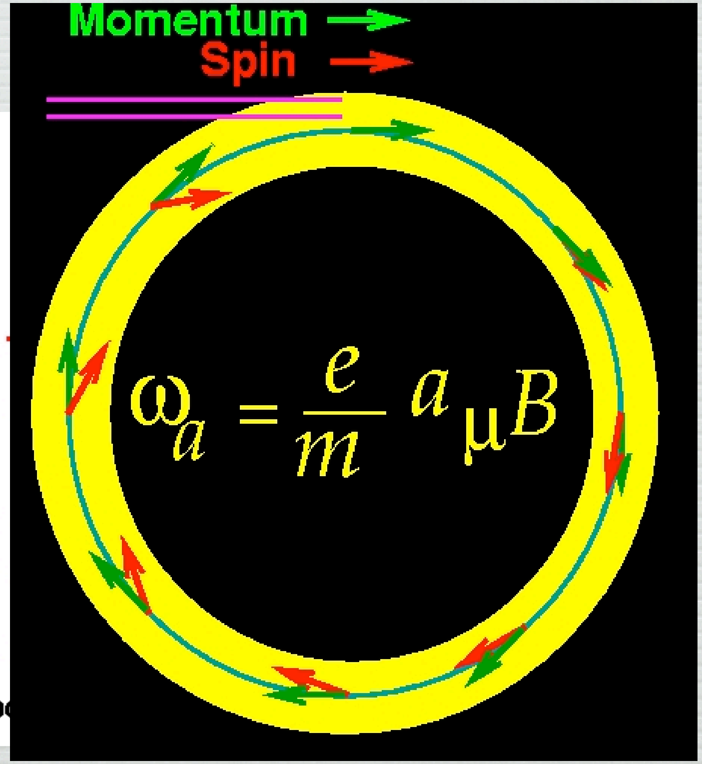
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

(g-2)/2

$\gamma_{\text{magic}} = 29.3$

$p_{\text{magic}} = 3.09\ \text{GeV/c}$





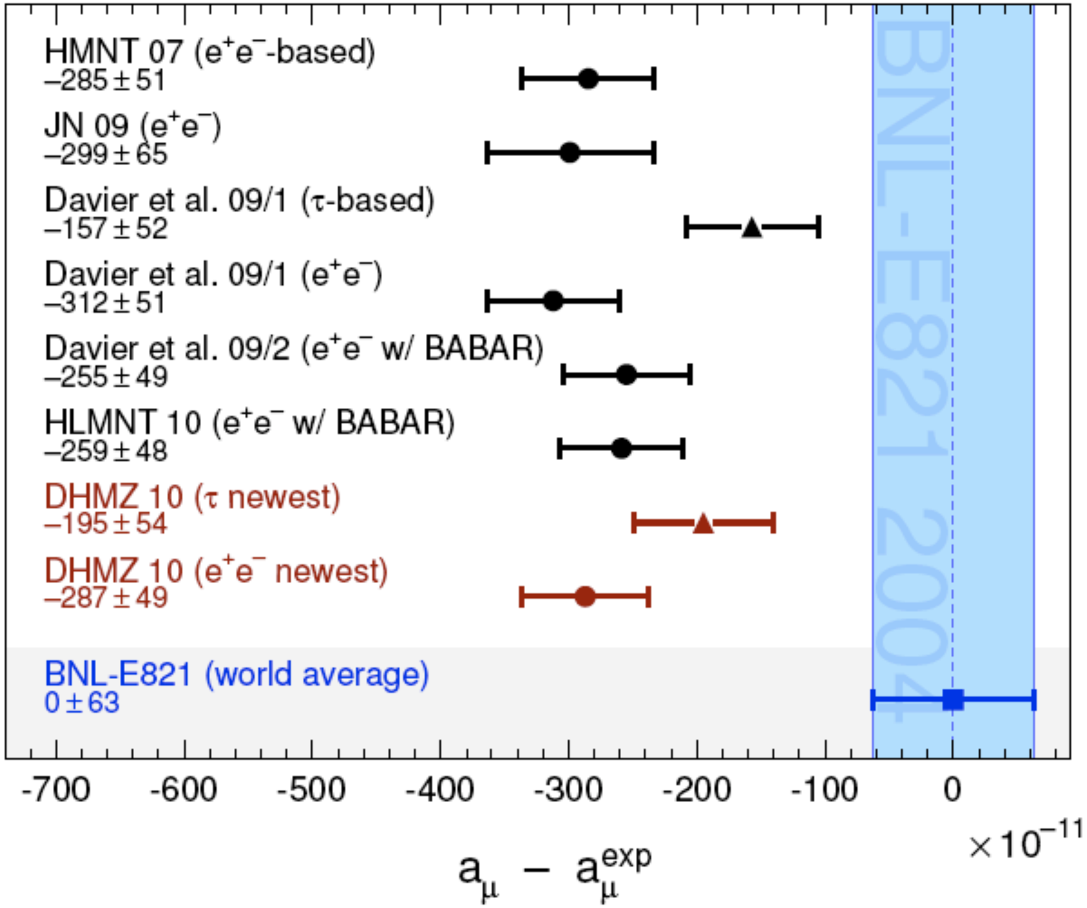
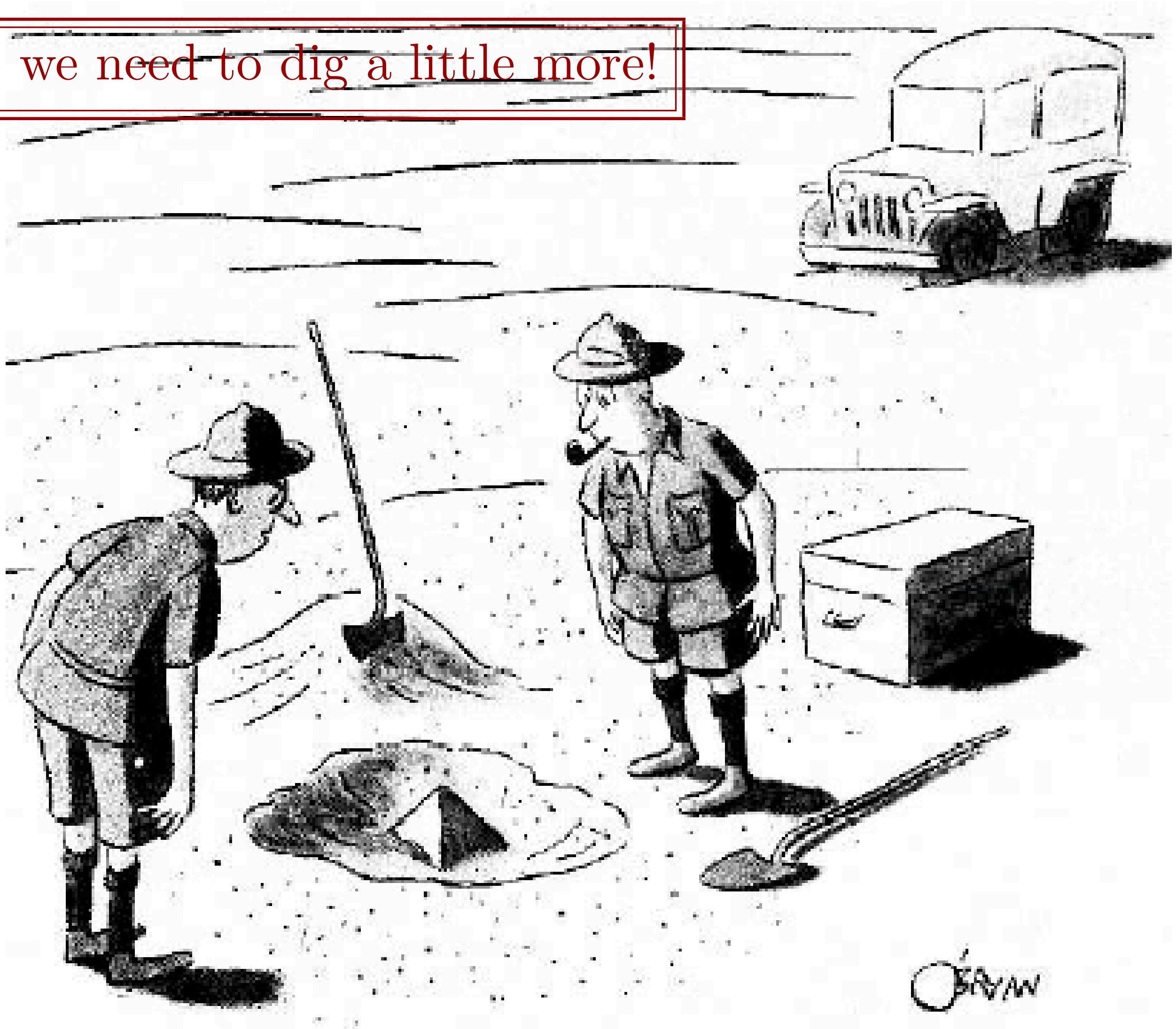


FIG. 9: Compilation of recent results for $a_\mu^{\rm SM}$ (in units of 10^{-11}), subtracted by the central value of the experimental average [12, 57]. The shaded vertical band indicates the experimental error. The SM predictions are taken from: this work (DHMZ 10), HLMNT (unpublished) [58] (e^+e^- based, including BABAR and KLOE 2010 $\pi^+\pi^-$ data), Davier *et al.* 09/1 [15] (τ-based), Davier *et al.* 09/1 [15] (e^+e^--based, not including BABAR $\pi^+\pi^-$ data), Davier *et al.* 09/2 [10] (e^+e^--based including BABAR $\pi^+\pi^-$ data), HMNT 07 [59] and JN 09 [60] (not including BABAR $\pi^+\pi^-$ data).

NOTE: $a_\mu^{LbL} = 105 \pm 26 \times 10^{-11}$

[Davier *et al*, 1010.4180]

$\boxed{\Delta a_\mu\text{: we need to dig a little more!}}$



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.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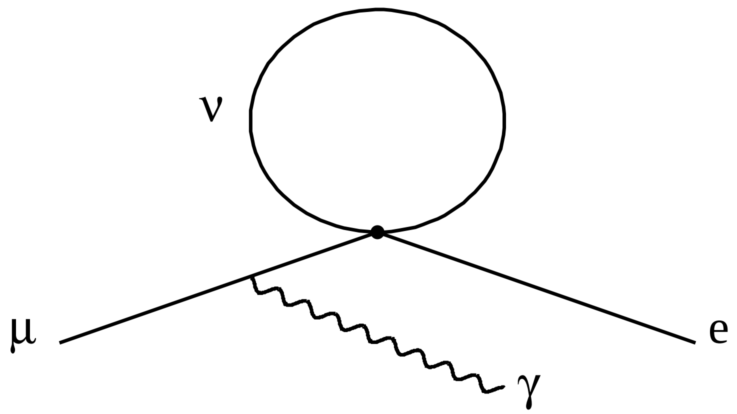
Illinois Tollway
OVERSIZE LOAD
EMMERT


EMMERT

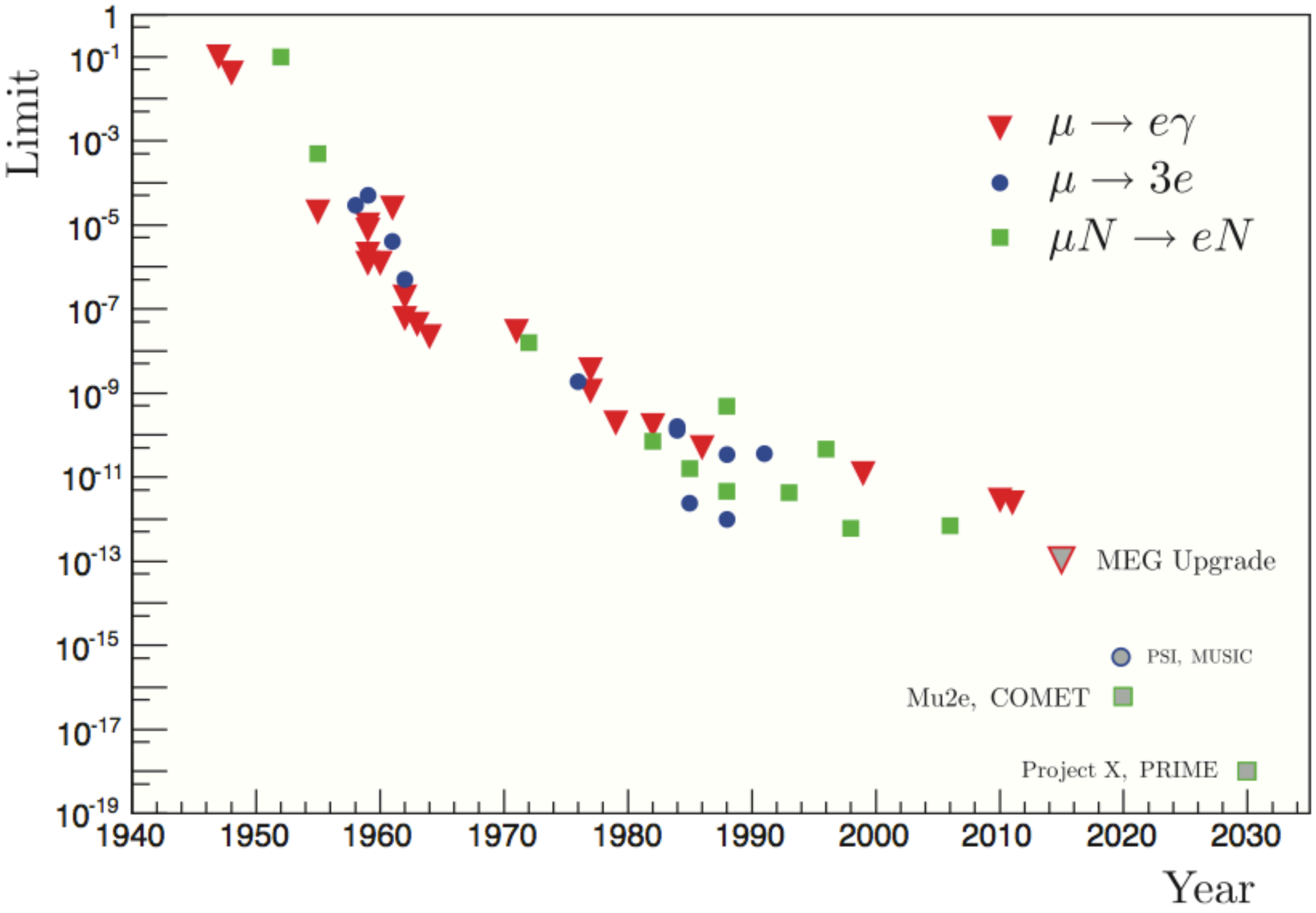
Ever since it was established that $\mu \to e\nu\bar{\nu}$, people have searched for $\mu \to e\gamma$, which was thought to arise at one-loop, like this:



The fact that $\mu \to e\gamma$ did not happen, led one to postulate that the two neutrino states produced in muon decay were distinct, and that $\mu \to e\gamma$, and other similar processes, were forbidden due to symmetries.

To this date, these so-called individual lepton-flavor numbers seem to be conserved in the case of charged lepton processes, in spite of many decades of (so far) fruitless searching…

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



[R. Bernstein, P. Cooper, arXiv 1307.5787]

Figure 3: The history of CLFV searches in muons (not including muonium.) One sees a steady improvement in all modes and then a flattening of the rate improvement throughout the 1990s. MEG has upgrade plans for the $\mu \to e\gamma$ search. The two next generations of $\mu N \to eN$, Mu2e/COMET at FNAL

SM Expectations?

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It vanishes because individual lepton-flavor number is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

But individual lepton-flavor number are NOT conserved– ν oscillations!

Hence, in the νSM (the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \to s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

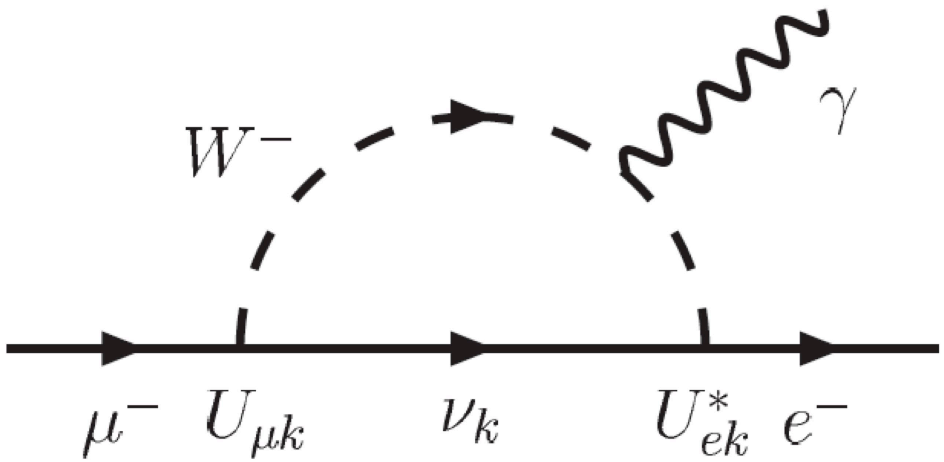
Unfortunately, we do not know the νSM expectation for charged lepton flavor violating processes → **we don't know the νSM Lagrangian !**

One contribution known to be there: active neutrino loops (same as quark sector).

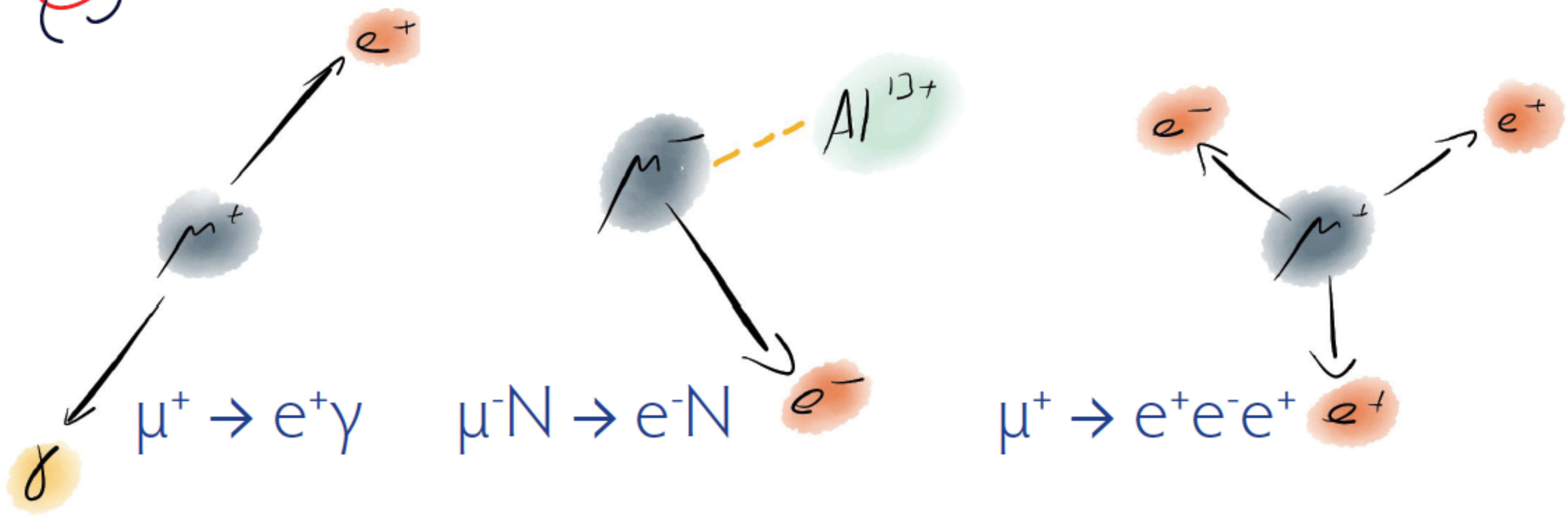
In the case of charged leptons, the **GIM suppression is very efficient**…

$$\text{e.g.: } Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,
$\Delta m^2_{1i} \equiv m^2_i - m^2_1$, $i = 2, 3$ are the neutrino mass-squared differences]



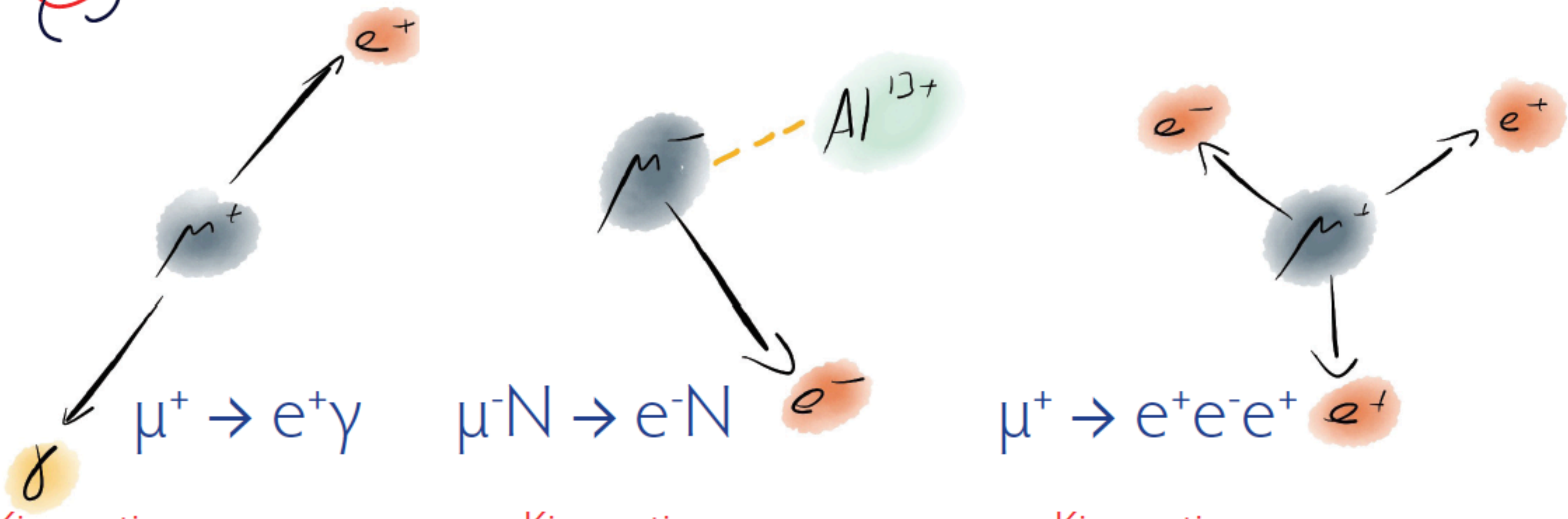
LFV Muon Decays: Experimental Situation



MEG (PSI)	SINDRUM II (PSI)	SINDRUM (PSI)
$B(\mu^+ \to e^+\gamma) < 5.7 \cdot 10^{-13}$	$B(\mu^- Au \to e^- Au) < 7 \cdot 10^{-13}$	$B(\mu^+ \to e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(2013)	(2006)	(1988)
upgrading	Mu2e/Comet	Mu3e

[Berger, talk at Lepton Moments 2014]

LFV Muon Decays: Experimental signatures



$\mu^+ \rightarrow e^+\gamma$ $\mu^-N \rightarrow e^-N$ $\mu^+ \rightarrow e^+e^-e^+$

Kinematics

- 2-body decay
- Monoenergetic e^+, γ
- Back-to-back

Background

- Accidental background

Kinematics

- Quasi 2-body decay
- Monoenergetic e^-
- Single particle detected

Background

- Decay in orbit
- Antiprotons, pions, cosmics

Kinematics

- 3-body decay
- Invariant mass constraint
- $\sum p_i = 0$

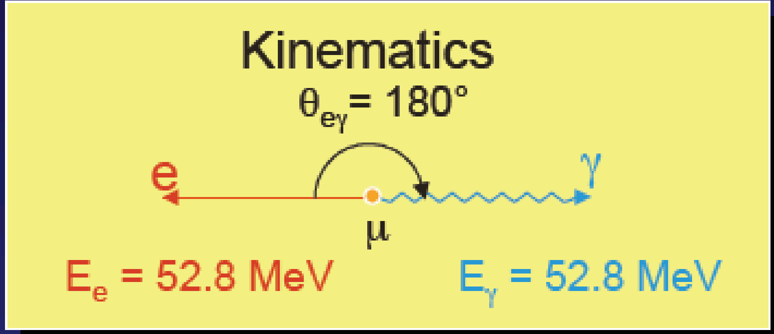
Background

- Radiative decay
- Accidental background

[Berger, talk at Lepton Moments 2014]

Principal Features of $\mu^+ \to e^+\gamma$ Experiment

- Stop μ^+ in thin target
  - Measure energies of e^+ (E_e) and γ (E_γ)
  - Measure angle between e^+ and γ ($\Delta\theta$)
  - Measure time between e^+ and γ (Δt)

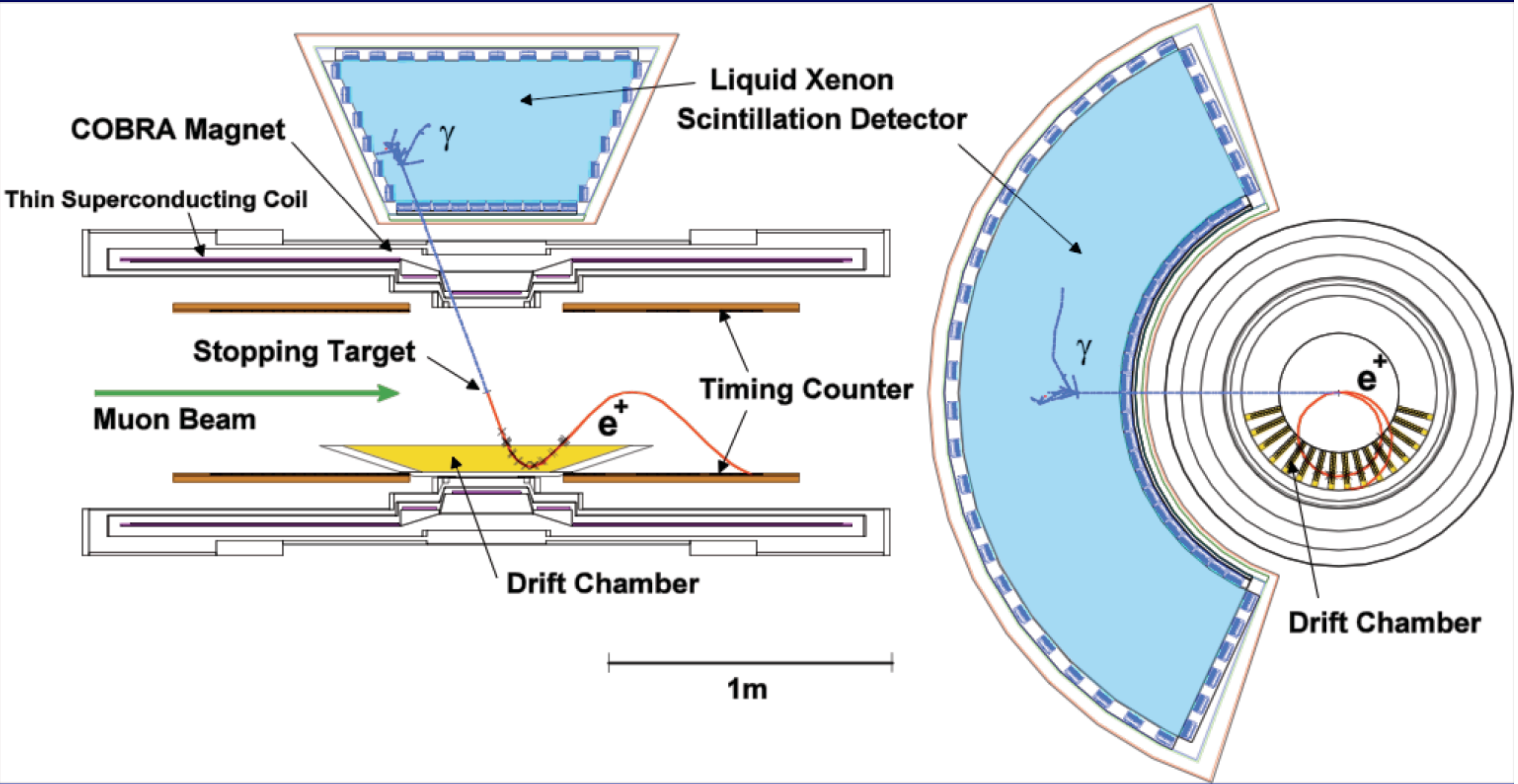


- Background from radiative decay – $\mu \to e\nu\nu\gamma$
  - Heavily suppressed for $E_\nu \to 0$, photon opposite electron
  - Not dominant background when rate high enough to reach 10^{-13} sensitivity

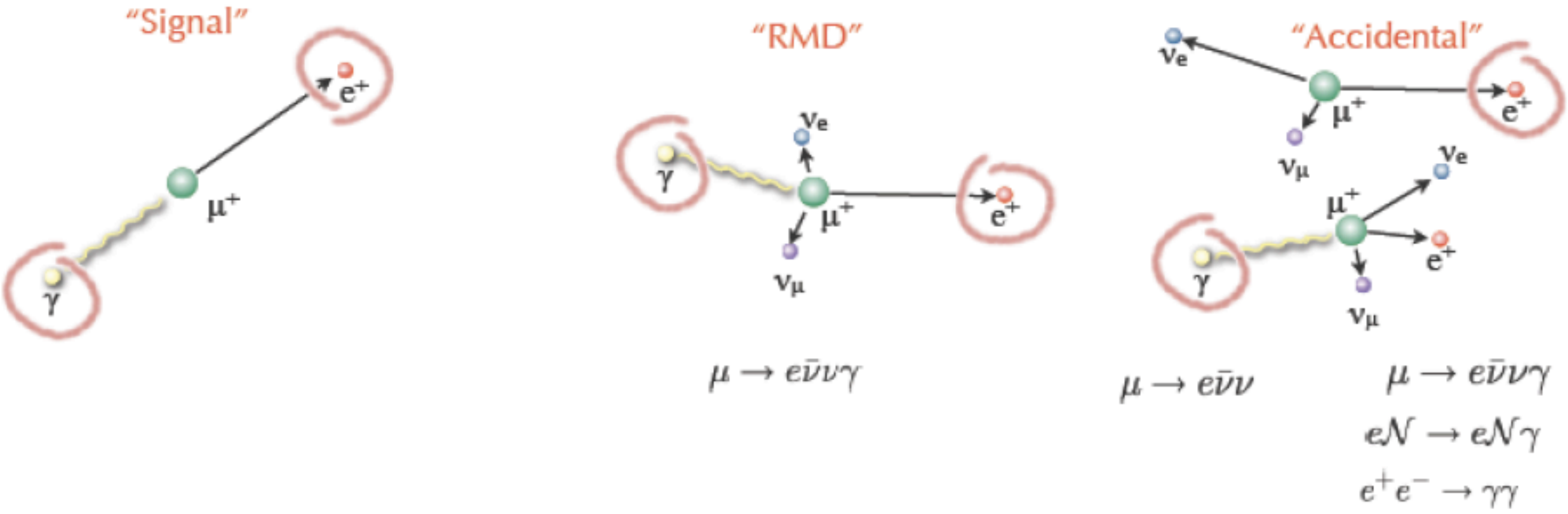
- Main source of background:
  - Accidental coincidences of e^+ from Michel decay ($\mu^+ \to e^+ \nu_e \nu_\mu$) + random γ from radiative decay or annihilation in flight
  - E_e distribution peaks near 53 MeV ($x = E_e / E_{max}$)
  - E_γ distribution in interval dy near y=1 given by $dN_\gamma \propto (1-y)dy$ ($y = E_\gamma / E_{max}$)

$\Rightarrow$ background/signal $\propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t \times (\Delta\theta)^2 \times$ Rate

The MEG Experiment



W. Molzon, UC Irvine NuFact 2006 - Status of the MEG Experiment August 28, 2006 5



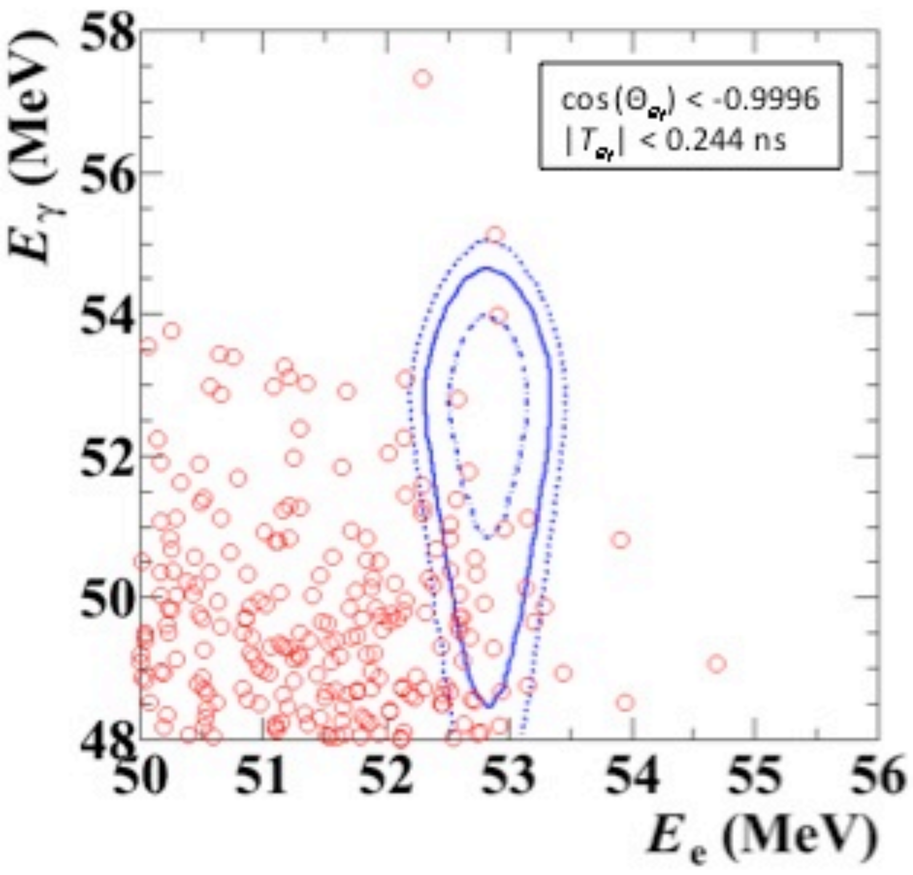
$\Uparrow$

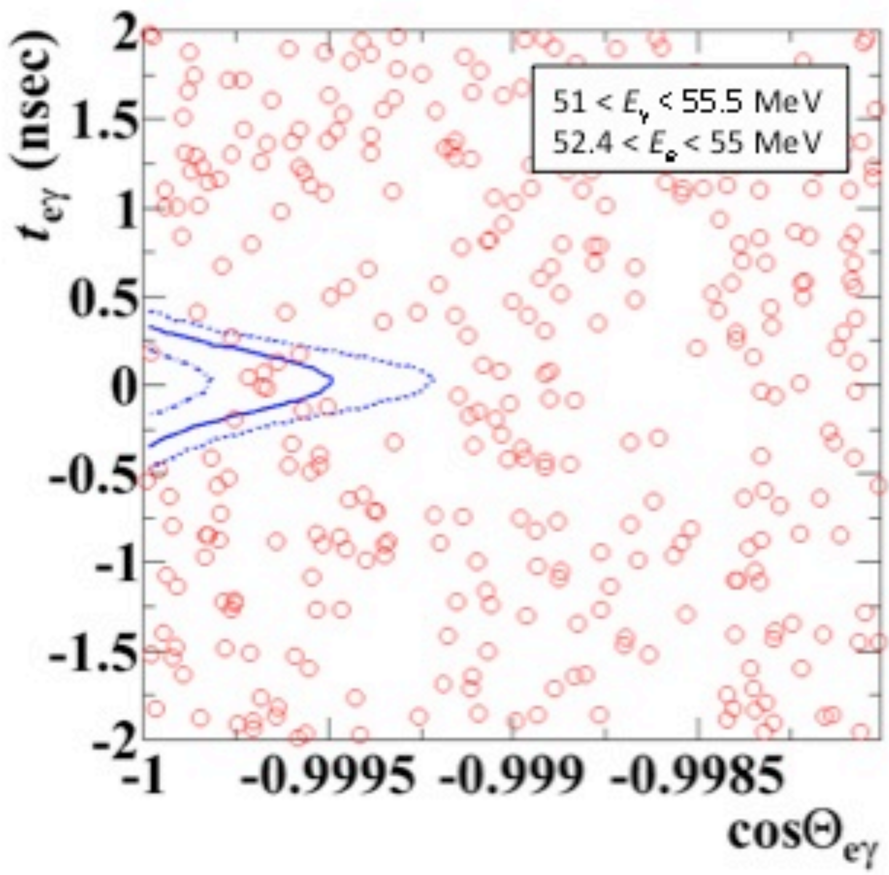
Dominant Background

PRL 110 (2013) 201801

Event distributions

Signal PDF contours at 1, 1.64 and 2 sigma (68%, 90% and 95%)





No excess of events in the signal region

Conclusion

Most recent analysis:

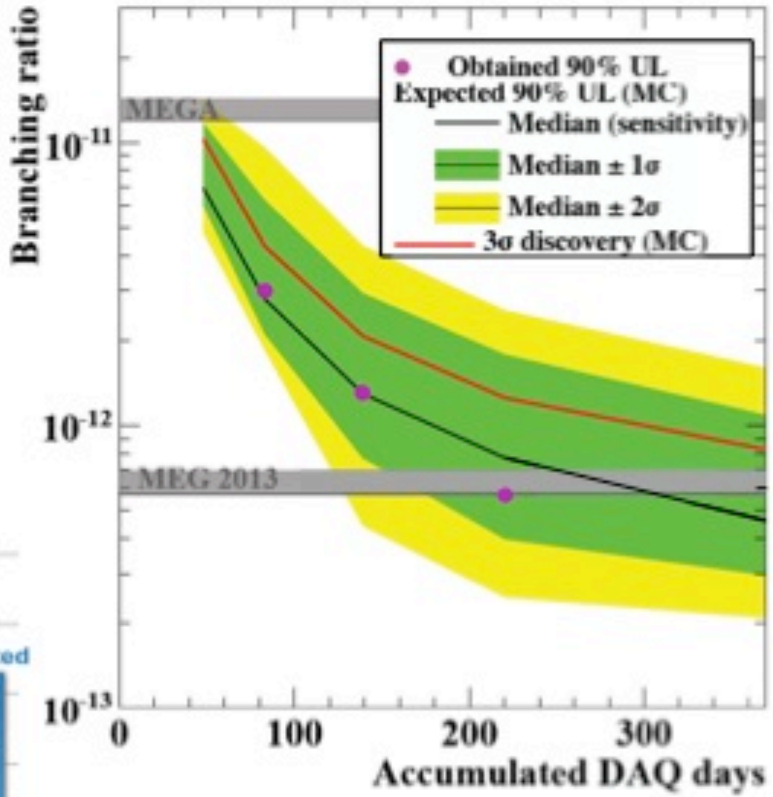
Combined 2009-2011 analysis did not show a significant excess of signal over background, resulting in a factor 4 improvement of the world's most stringent BR($\mu \to e\gamma$) upper limit:

$$\mathrm{Br}(\mu^+ \to e^+\gamma) \ < \ 5.7 \cdot 10^{-13} \ (90\% \ \mathrm{C.L.})$$

Outlook:

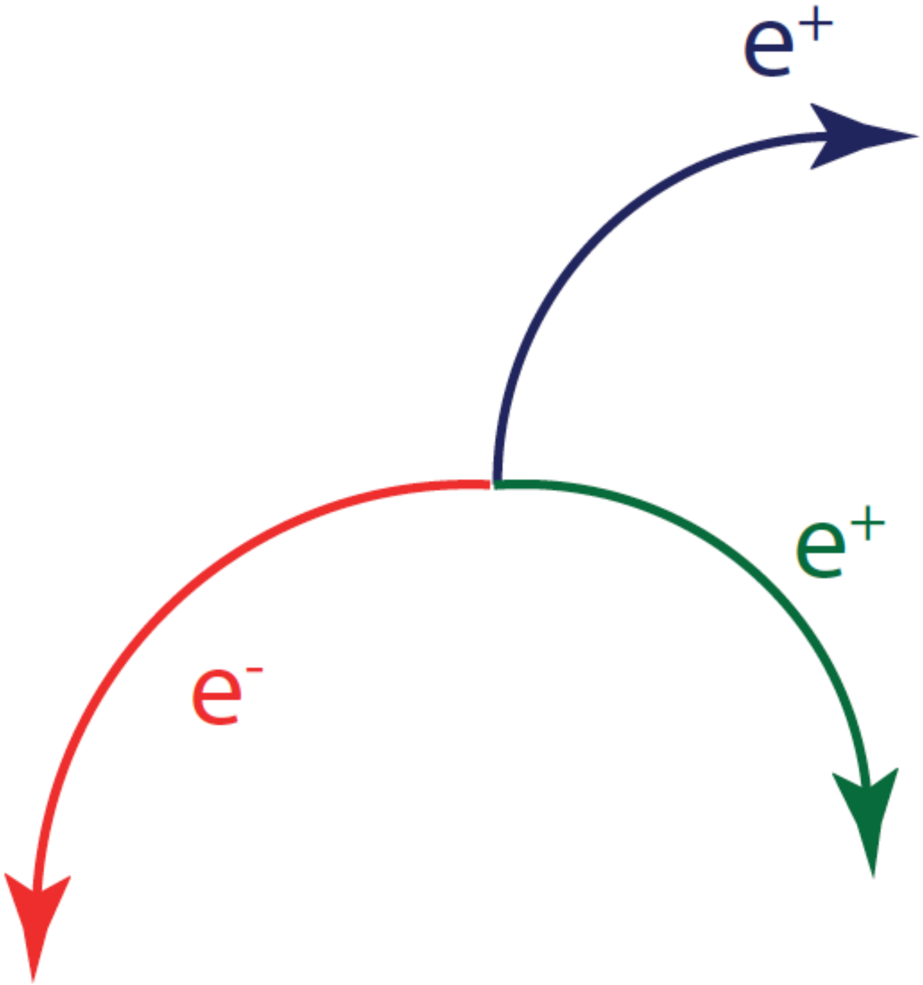
- Data taking finished September 2013
- Total statistics incl. 2012+2013 data is expected to double
- New results coming end of this year

- Observed BR limits & sensitivity:



But that's not all..

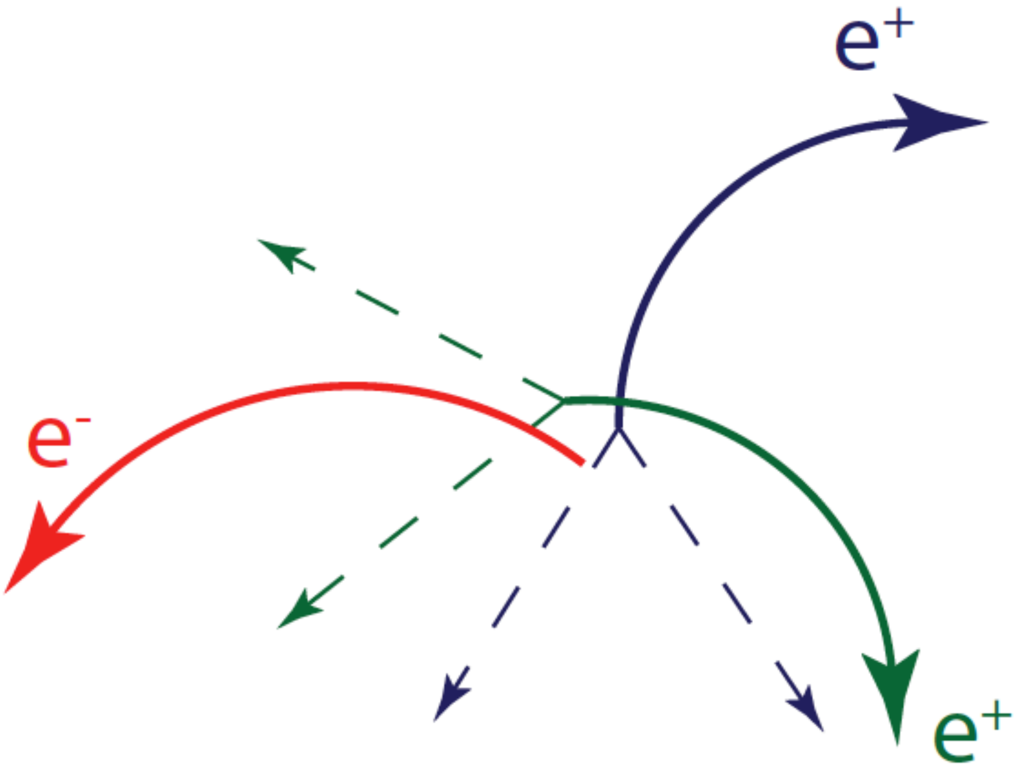
The signal



- $\mu^+ \to e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: $\frac{1}{2}\, m_\mu$ = 53 MeV/c

[Berger, talk at Lepton Moments 2014]

Accidental Background

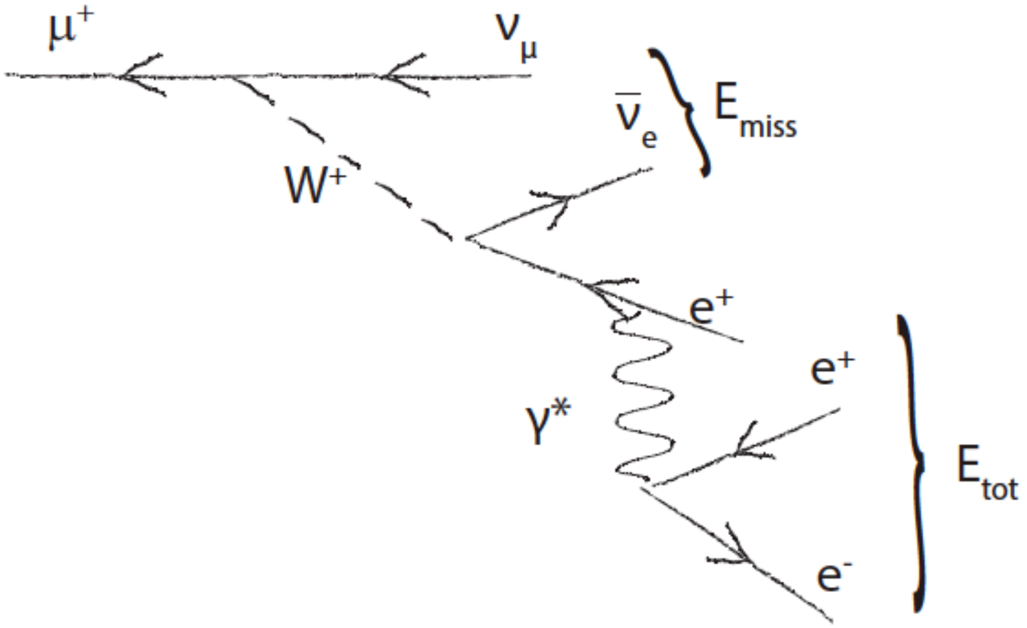


- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction

- Need very good timing, vertex and momentum resolution

[Berger, talk at Lepton Moments 2014]

Internal conversion background

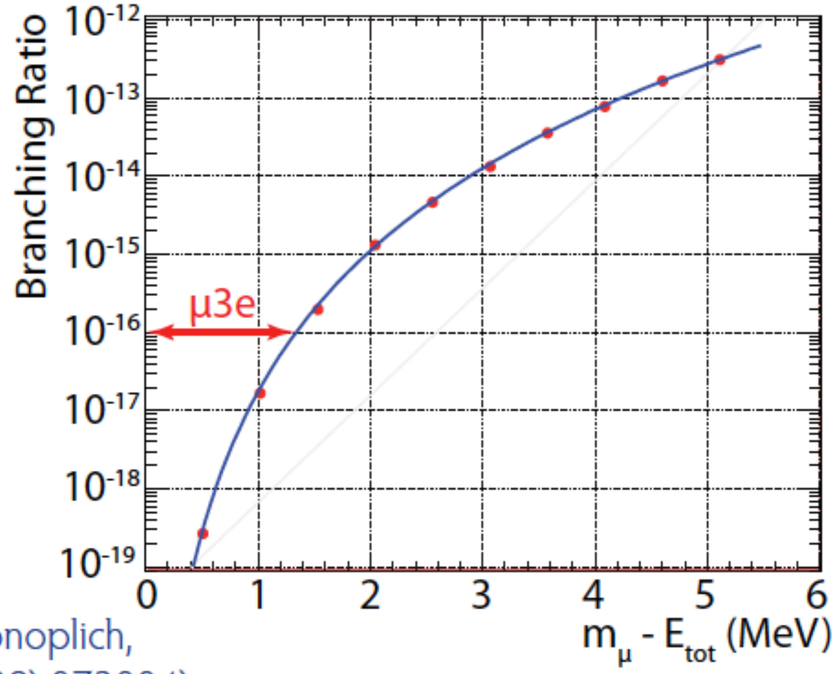


- Allowed radiative decay with internal conversion:

$$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos

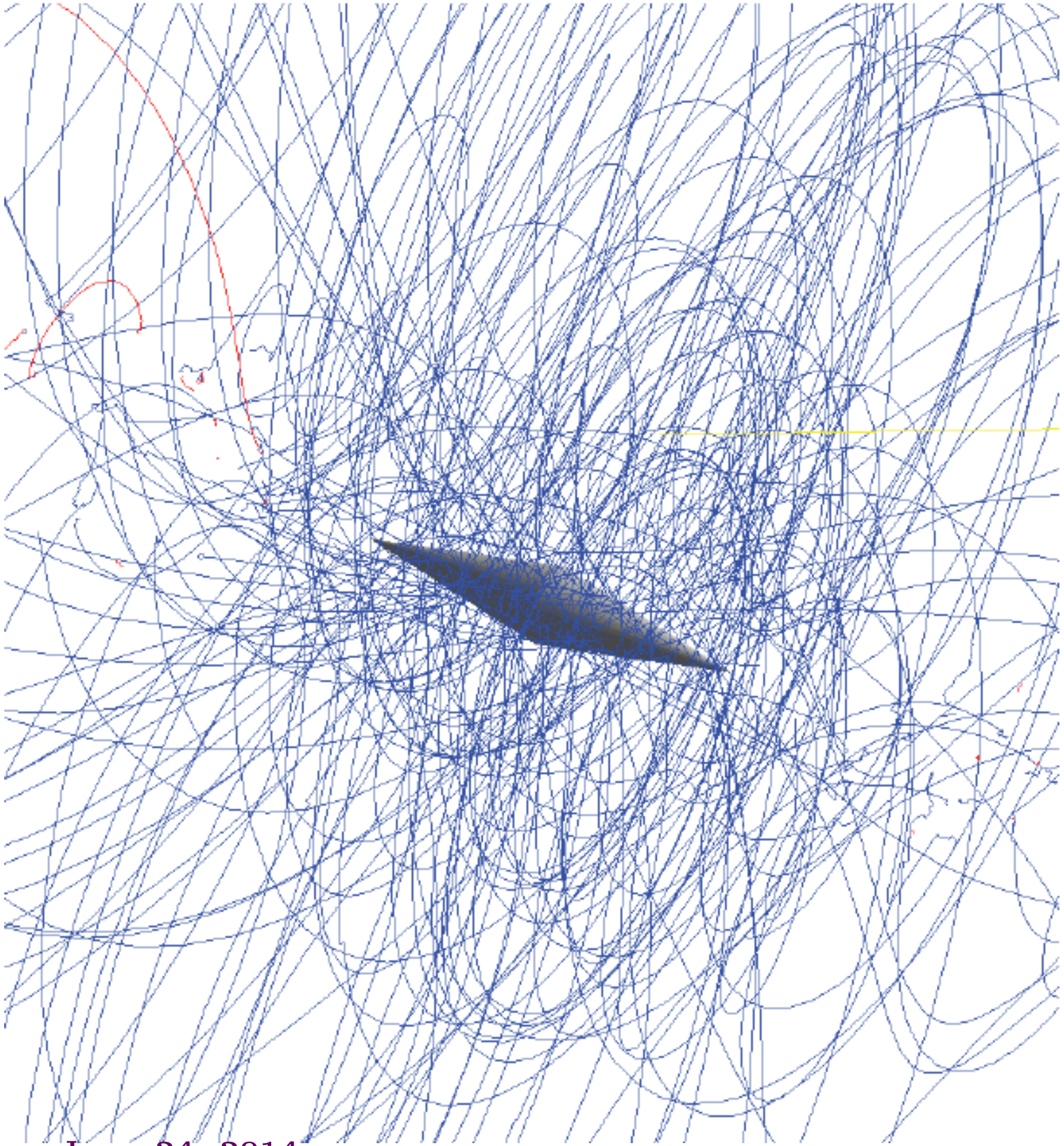
- Need excellent momentum resolution



(R. M. Djilkibaev, R. V. Konoplich, Phys.Rev. D79 (2009) 073004)

[Berger, talk at Lepton Moments 2014]

Detector Technology



- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)

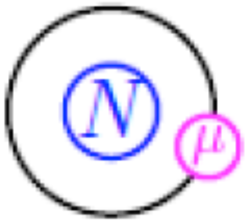
- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)

[Berger, talk at Lepton Moments 2014]

Muon to Electron Conversion

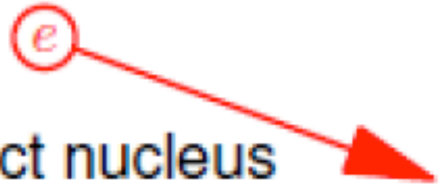
Charged lepton flavor violating process

Nucleus nearby for conservation of momentum and energy



Initial state:
muonic atom at rest

No neutrinos in final state



Final state:
electron + intact nucleus

- Signal is monoenergetic electron

$$E_e = m_\mu - E_b - E_{\text{recoil}} \approx 104.97\ \text{MeV for Al}$$

- Conventional signal normalization

$$R_{\mu e} = \frac{\Gamma[\mu^- + N \to e^- + N]}{\Gamma[\mu^- + N \to \text{all captures}]}$$

[J. Miller, talk at Lepton Moments 2014]

Muon to Electron Conversion: Present and Future Precision

Current limits: $$R_{\mu e} = \frac{\mu^- Au \to e^- Au}{\mu^- Au \to \text{capture}} < 7\text{x}10^{-13} \text{ (SINDRUM II)}$$

Also: $$R_{\mu e} = \frac{\mu^- Ti \to e^- Ti}{\mu^- Ti \to \text{capture}} < 4.3\text{x}10^{-12} \text{ (SINDRUM II)}$$

$$R_{\mu e} = \frac{\mu^- Ti \to e^- Ti}{\mu^- Ti \to \text{capture}} < 4.6\text{x}10^{-12} \text{ (TRIUMF)}$$

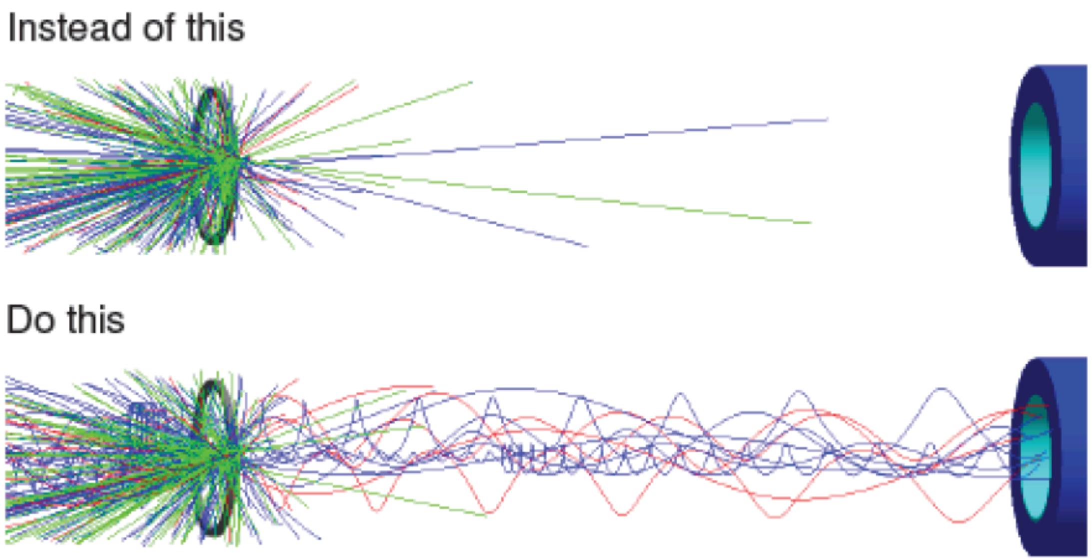
Mu2e goal: $$R_{\mu e} = \frac{\mu^- Al \to e^- Al}{\mu^- Al \to \text{capture}} < 6\text{x}10^{-17} \text{ (90\% c.l.)}$$

four orders of magnitude improvement over current limit!

[J. Miller, talk at Lepton Moments 2014]

- Increase in sensitivity by 10^4
  - Mu2e single event sensitivity goal 2.5×10^{-17}
- Mu2e needs ~few x 10^{17} stopped muons
  - Best available beam line ~ 10^8 Hz (PSI 1.3 MW beam)
  - Mu2e goal ~few x 10^{10} Hz
  - We are not proposing a 1 GW beam…

Develop a more efficient muon beamline

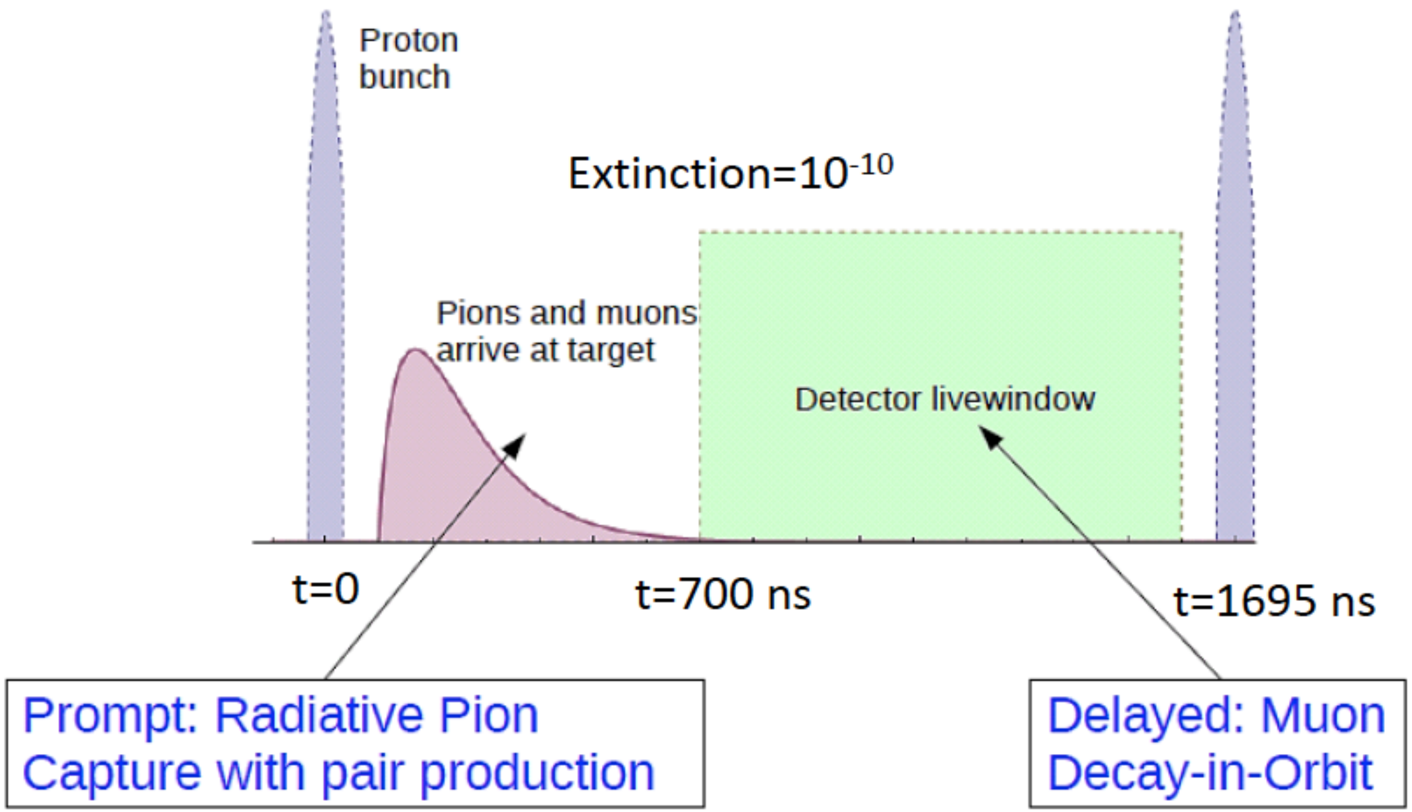


Solenoidal B field confines soft pions. Collect their decay muons.
Mu2e: > 10^{10} Hz stopped muons from only 8 kW of beam of protons

[J. Miller, talk at Lepton Moments 2014]

The two most dangerous backgrounds have very different timing properties

The FNAL accelerator complex produces proton beams with a pulsed structure



Also low energy backgrounds from muon captures In stopping target. Per capture: ~1.2 neutrons, ~0.1 protons, ~2 gammas

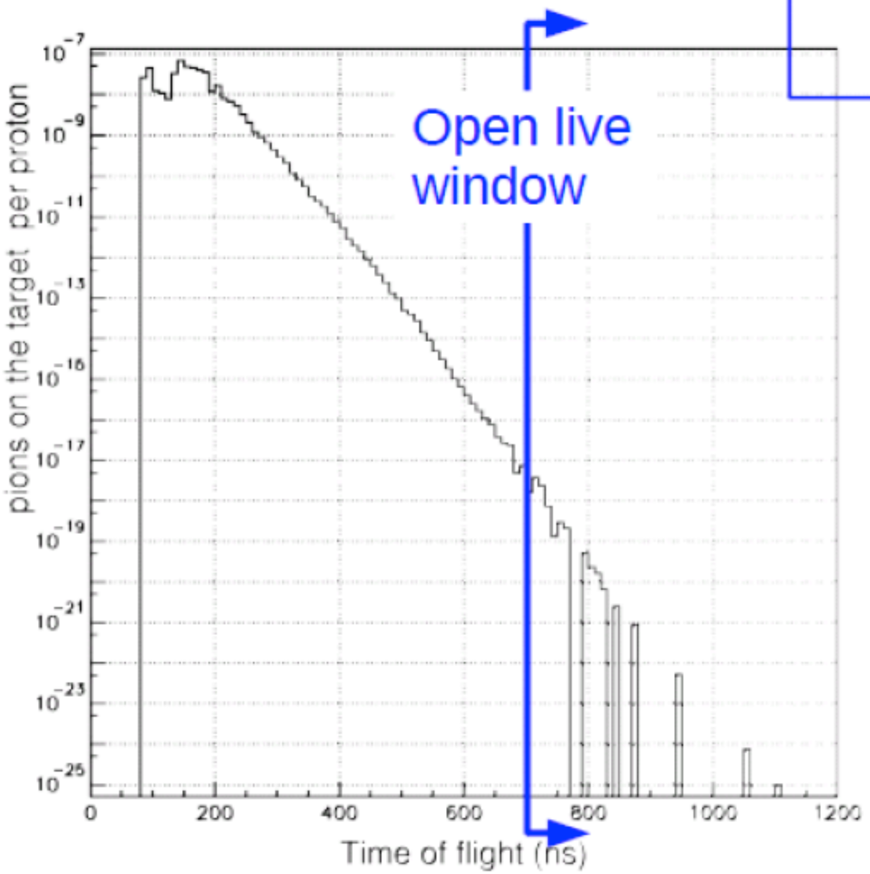
[J. Miller, talk at Lepton Moments 2014]

Radiative Pion Capture

can produce electrons near the conversion energy

$$\pi^- A(Z,N) \to \gamma A(Z-1,N+1)^*$$

$\gamma \to e^+e^-$



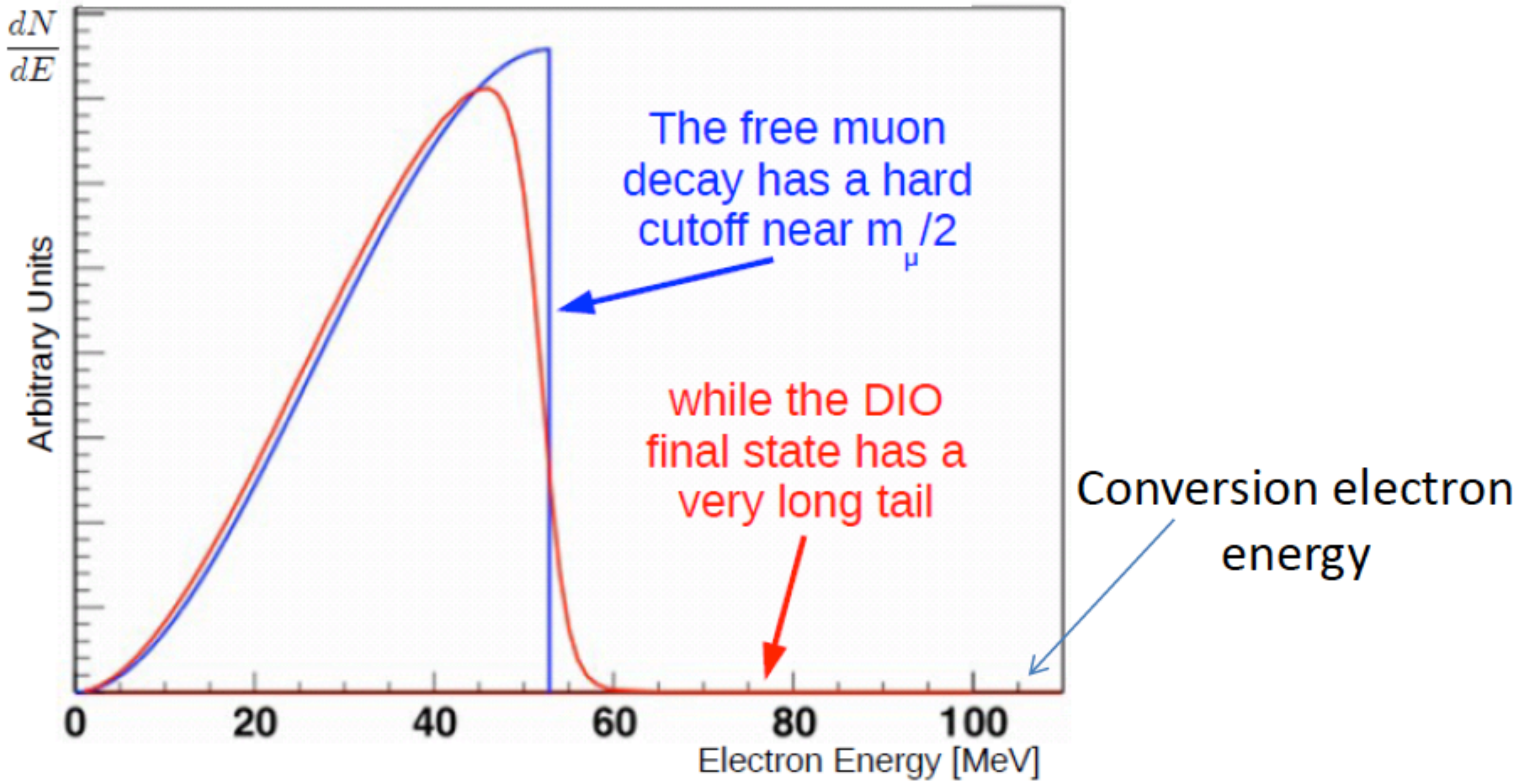
The electron spectrum extends out to nearly m_π=139.6 MeV

This (and other) prompt backgrounds are eliminated by keeping the DAQ dead until the background rate has fallen below some threshold.

[J. Miller, talk at Lepton Moments 2014]

Decay-in-Orbit is the major source of delayed background in the live window

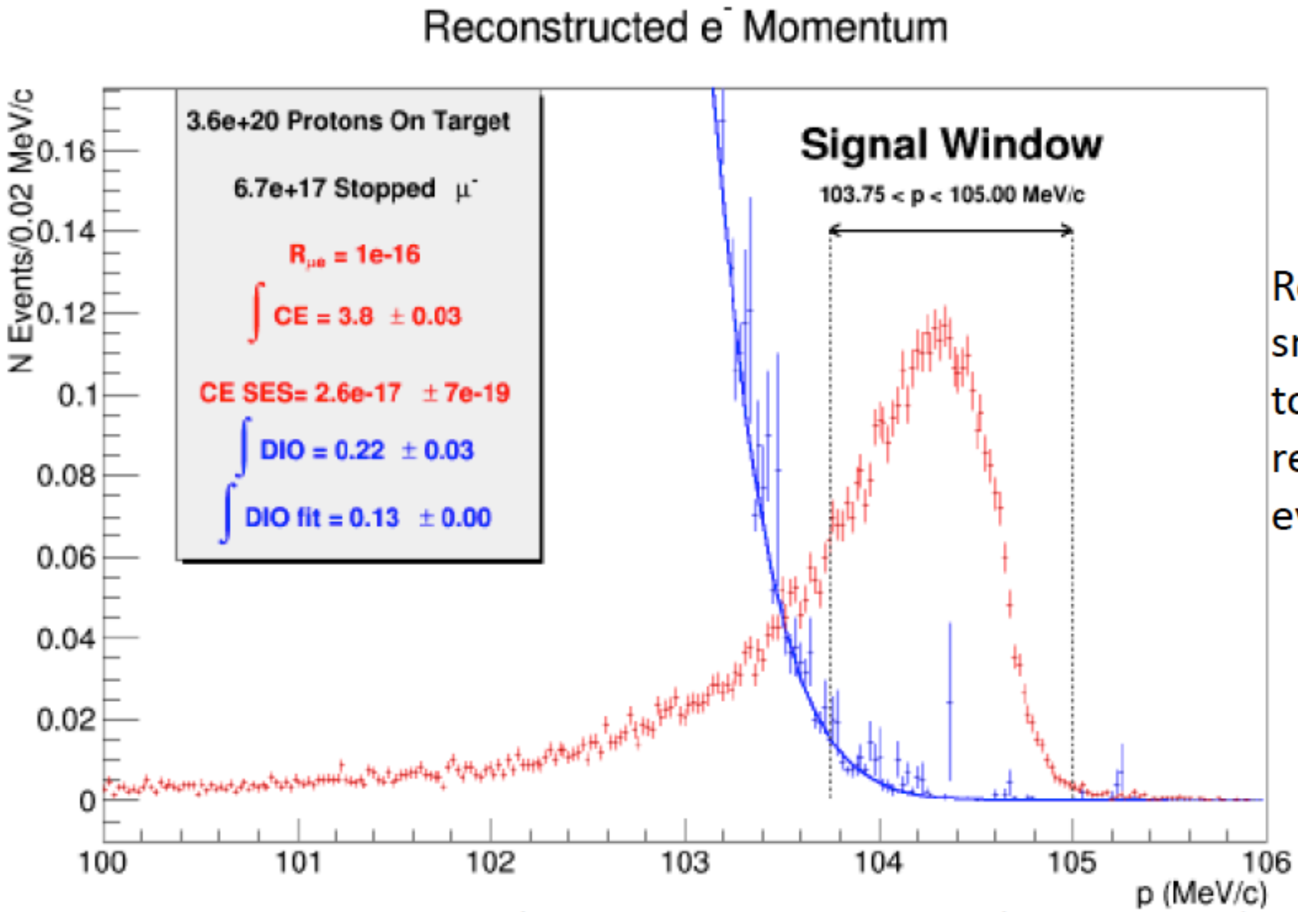
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$A(Z,N)\mu^- \rightarrow A(Z,N)e^- \nu_\mu \bar{\nu}_e$$



[J. Miller, talk at Lepton Moments 2014]

Simulation of DIO + conversion electron energy distributions

- *Assuming* $R_{\mu e}=10^{-16}$
- FWHM ~ 1 MeV, ~ 4 events in 103.7 MeV<E< 105 MeV)



Realistic scattering losses smear the distributions to lower energy, while resolution can push events to higher energy

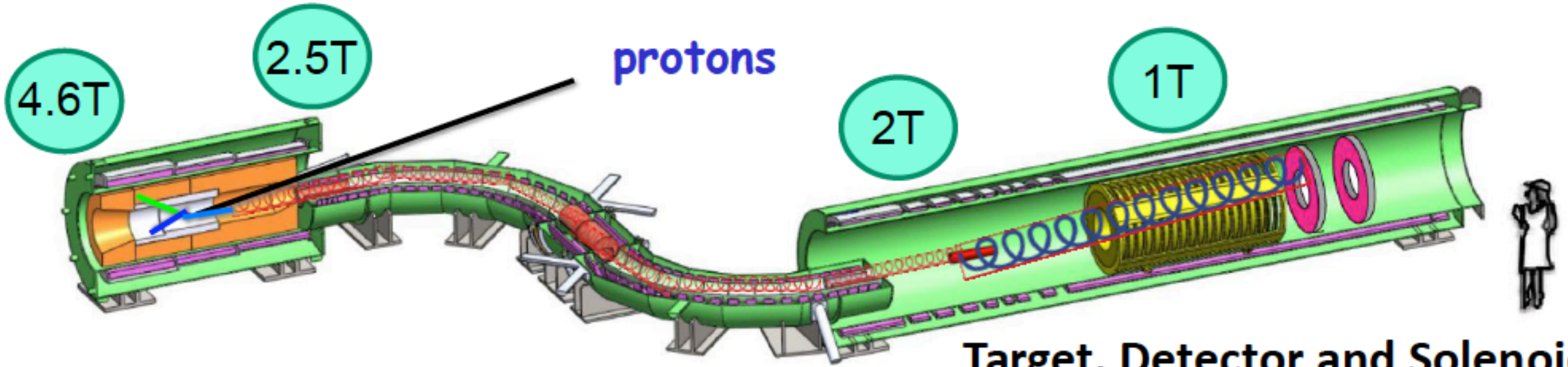
DIO Spectrum: A. Czarnecki, X. Tormo, W. Marciano, Phys. Rev. D84 (2011) 013006

[J. Miller, talk at Lepton Moments 2014]

Mu2e Overview

Production Target / Solenoid (PS)- 4m long x 1.5 m dia

- Proton beam strikes target, producing pions which decay to muons
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons



Target, Detector and Solenoid (DS)- 11m long x 2m dia

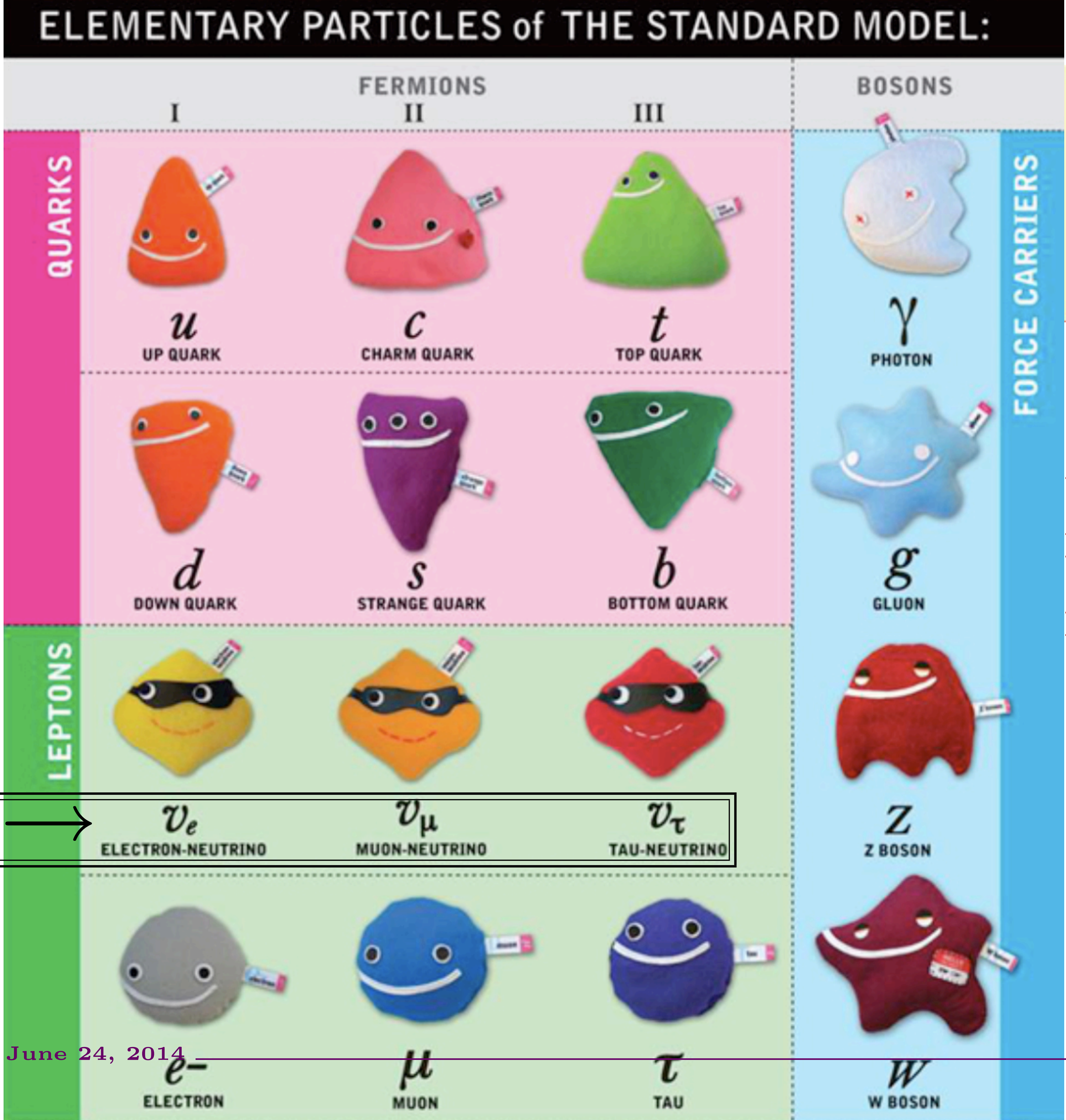
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter

Transport Solenoid (TS)- 13m long x 50 cm dia

Selects low momentum, negative muons
Antiproton absorber in the mid-section

Delivers ~0.002 stopped muons per 8 GeV proton

[J. Miller, talk at Lepton Moments 2014]



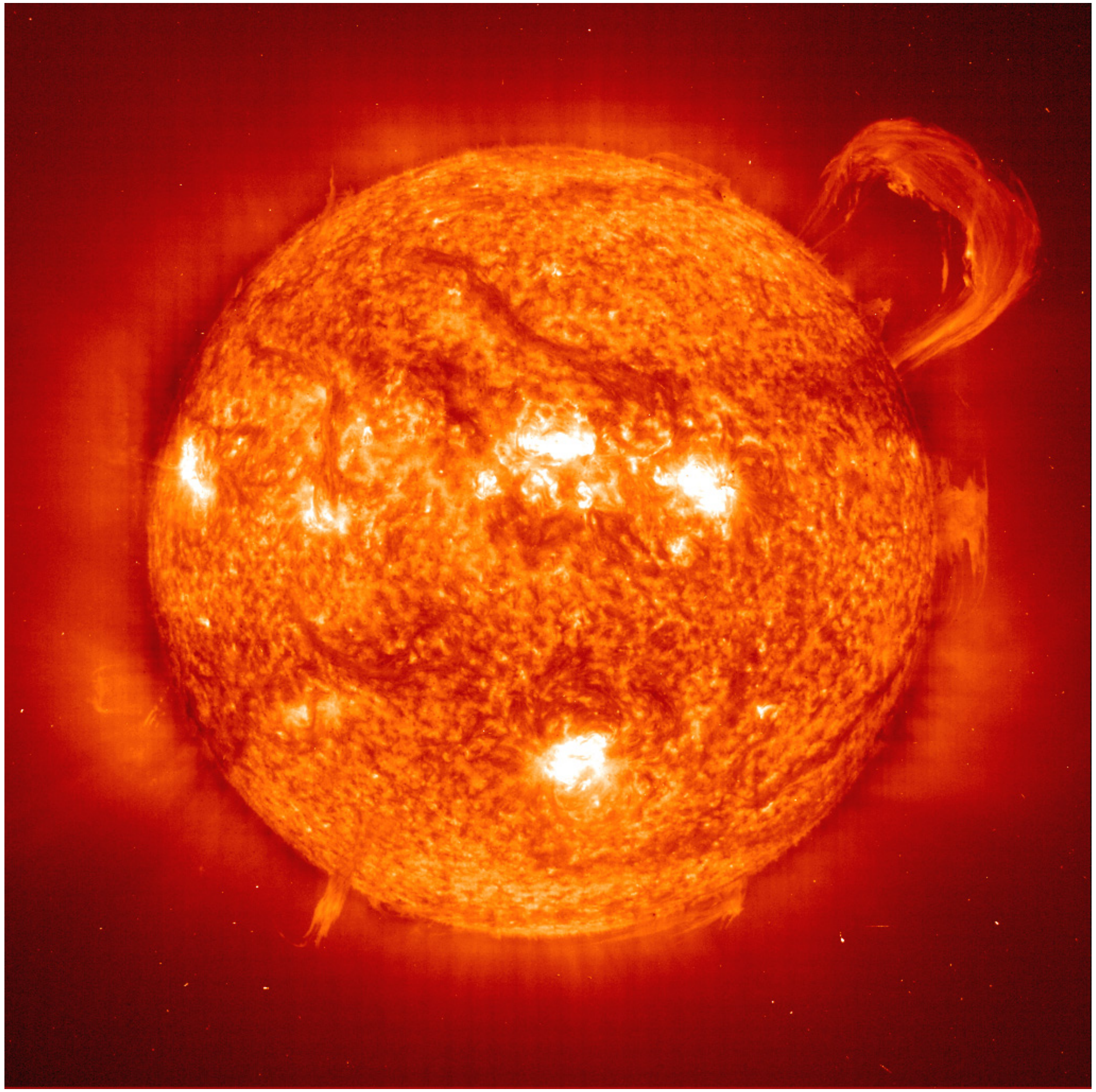
Neutrinos are Among a Handful of Known Fundamental, Point-Like Particles.

$$\text{neutrino} = \nu$$

('nu')

http://www.particlezoo.net

Neutrinos are Very, Very Abundant.

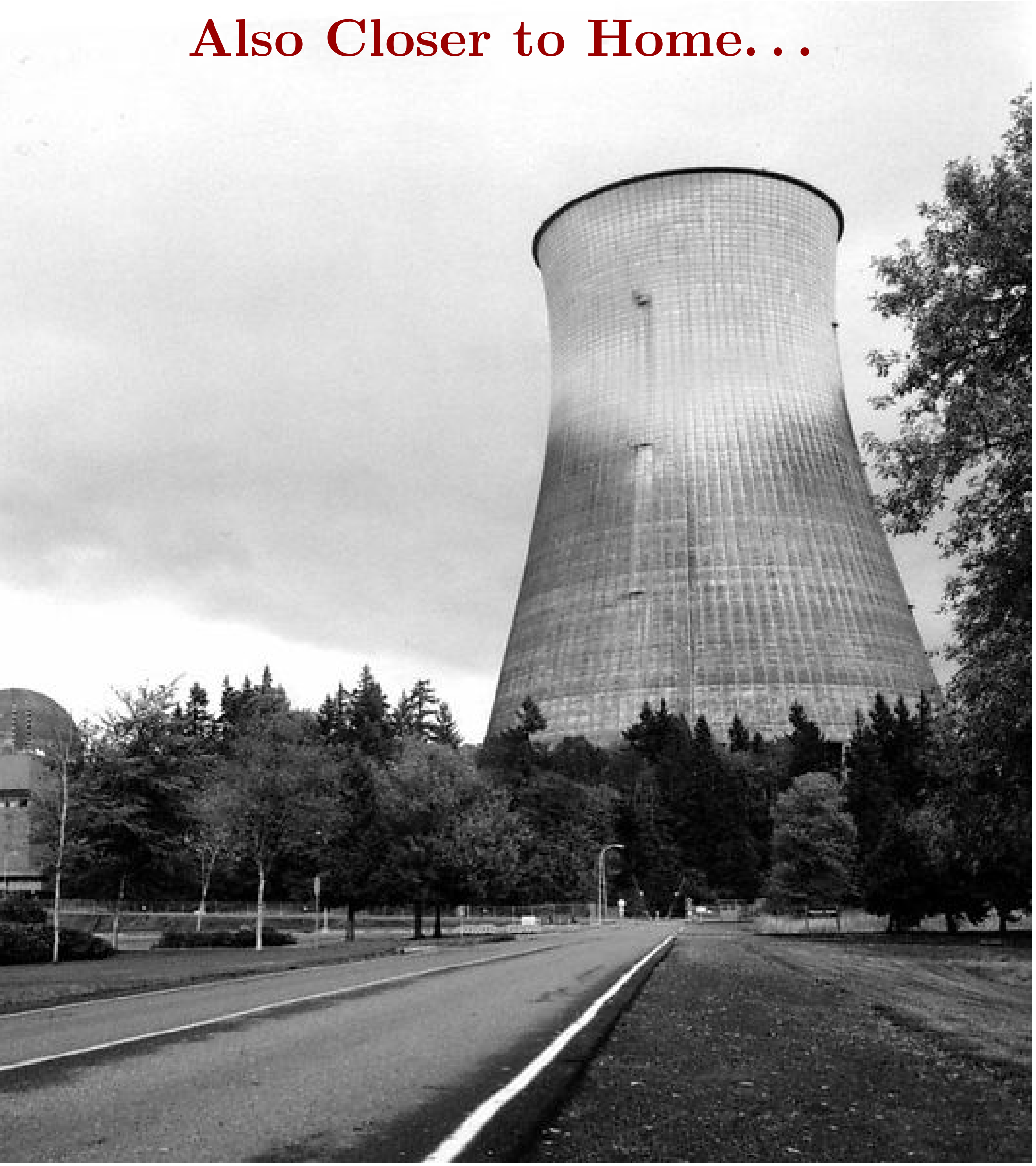


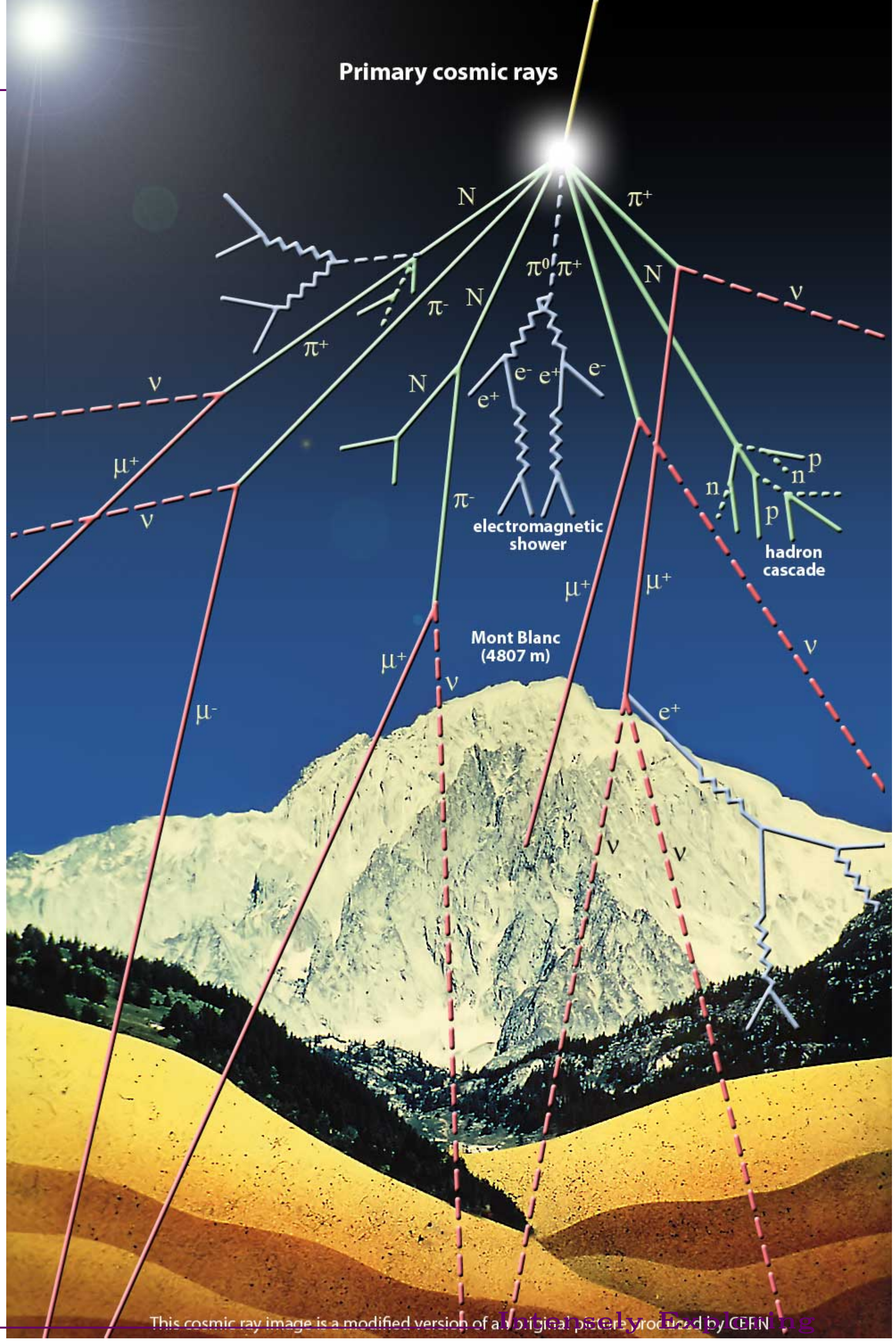
Reaction	Termination (%)	Neutrino Energy (MeV)
$p+p\to{}^2\mathrm{H}+e^+ + \nu_e$	99.96	<0.423
$p+e^- + p\to{}^2\mathrm{H}+\nu_e$	0.044	1.445
${}^2\mathrm{H}+p\to{}^3\mathrm{He}+\gamma$	100	–
${}^3\mathrm{He}+{}^3\mathrm{He}\to{}^4\mathrm{He}+p+p$	85	–
${}^3\mathrm{He}+{}^4\mathrm{He}\to{}^7\mathrm{Be}+\gamma$	15	–
${}^7\mathrm{Be}+e^-\to{}^7\mathrm{Li}+\nu_e$	15	0.863(90%) 0.386(10%)
${}^7\mathrm{Li}+p\to{}^4\mathrm{He}+{}^4\mathrm{He}$		–
${}^7\mathrm{Be}+p\to{}^8\mathrm{B}+\gamma$	0.02	–
${}^8\mathrm{B}\to{}^8\mathrm{Be}^* + e^+ + \nu_e$		<15
${}^8\mathrm{Be}\to{}^4\mathrm{He}+{}^4\mathrm{He}$		–
${}^3\mathrm{He}+p\to{}^4\mathrm{He}+e^+ + \nu_e$	0.00003	<18.8

Note: Adapted from Ref. 12. Please refer to Ref. 12 for a mor
nation.

around 100 billion go through your thumb every second!

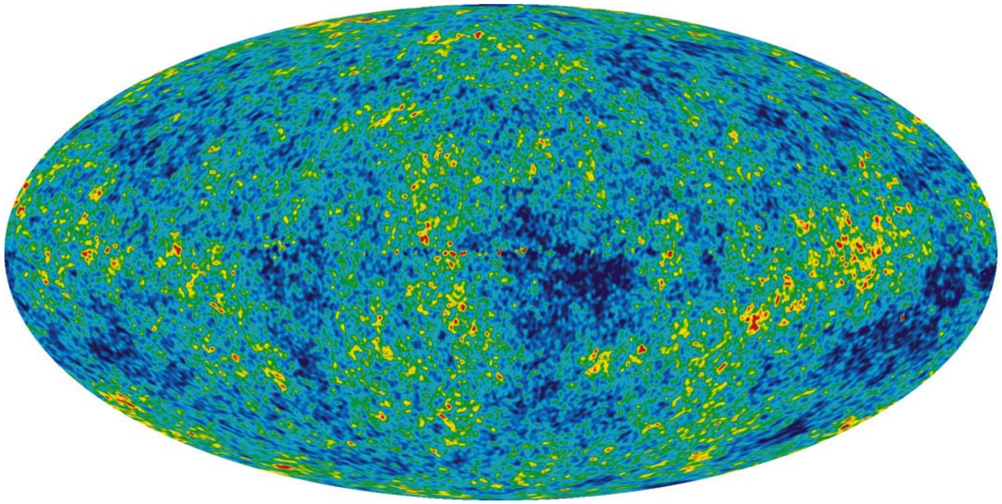
Also Closer to Home...

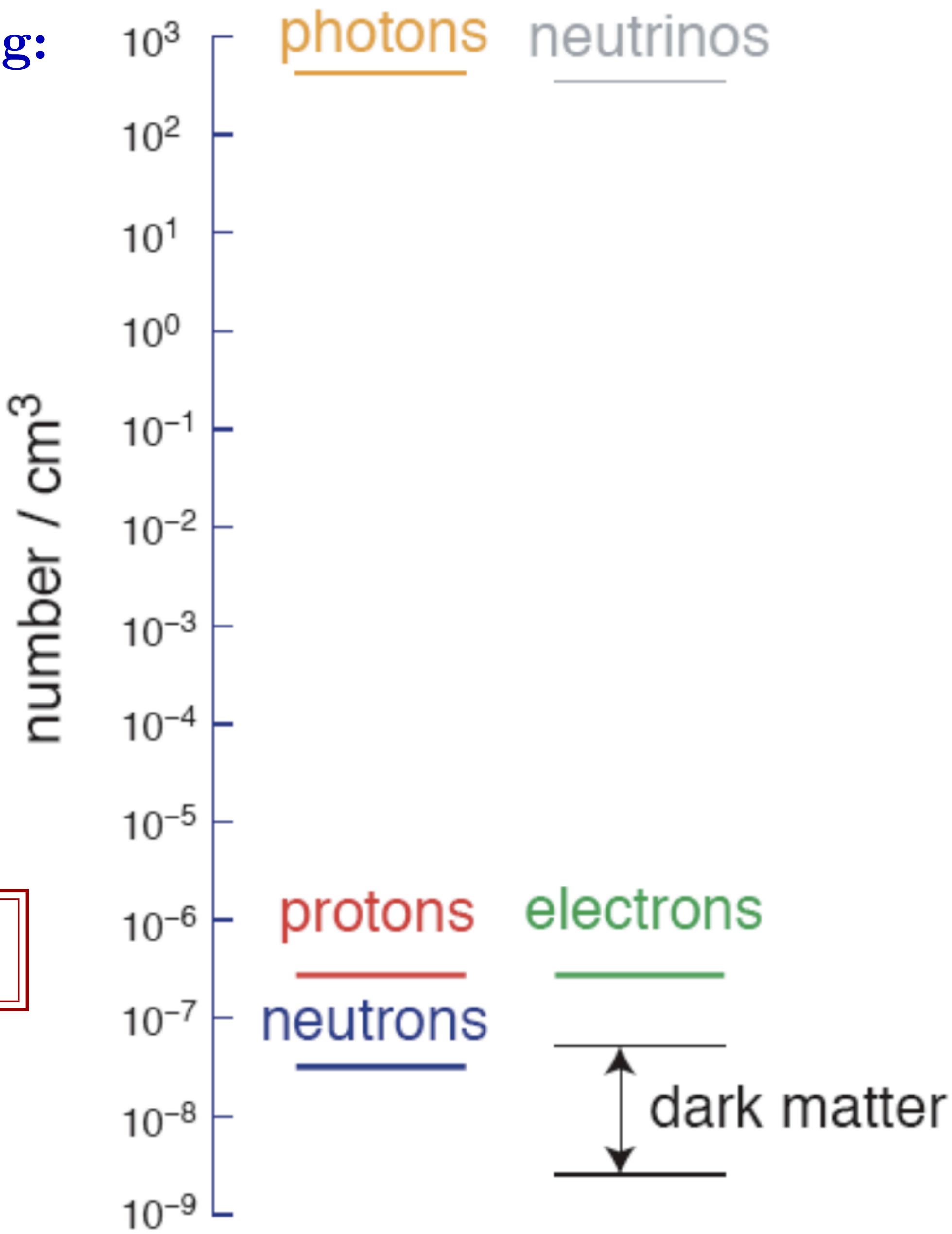




Supernova: 100 times more energy released in the form of neutrinos!

Neutrinos are Relics of the Big Bang:





Neutrinos are Everywhere

However, Neutrinos Are Really Hard To Detect:

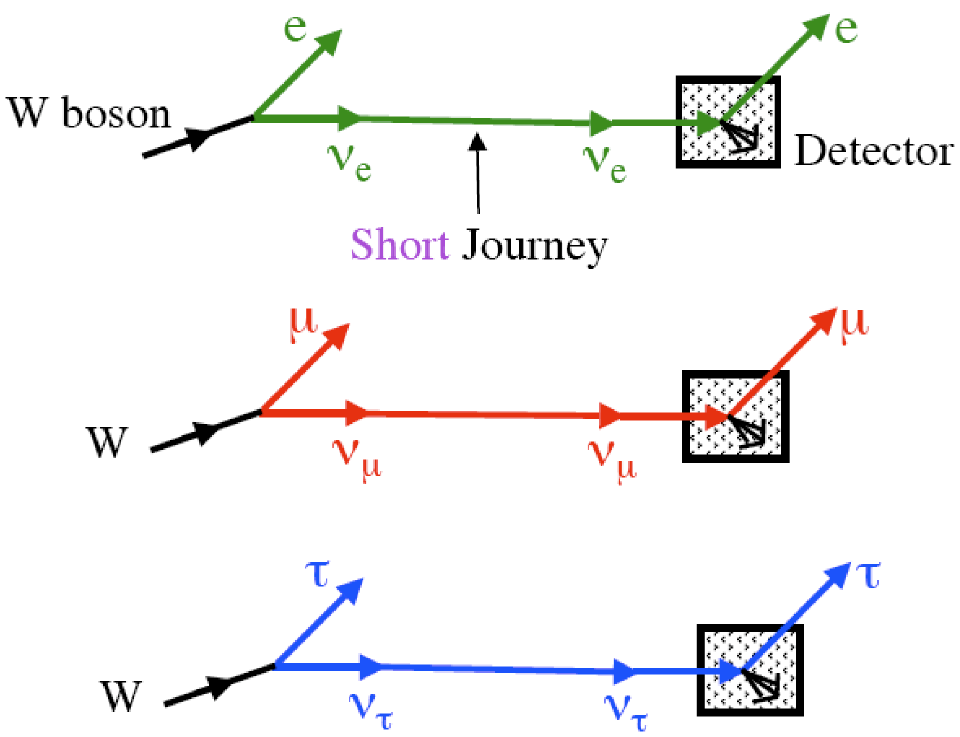
Neutrinos have no charge (unlike, say, the electrons) and don't interact via the strong nuclear forces (unlike, say, a neutron).

They interact only via the WEAK force – which, as it turns out, is really weak.

You need a wall of lead as thick as the solar system in order to stop a neutrino produced in the Sun!

How did we get around this? With lots and lots of neutrinos, and really big detectors!

Until recently ($\sim$ 1998), this is how we pictured neutrinos:



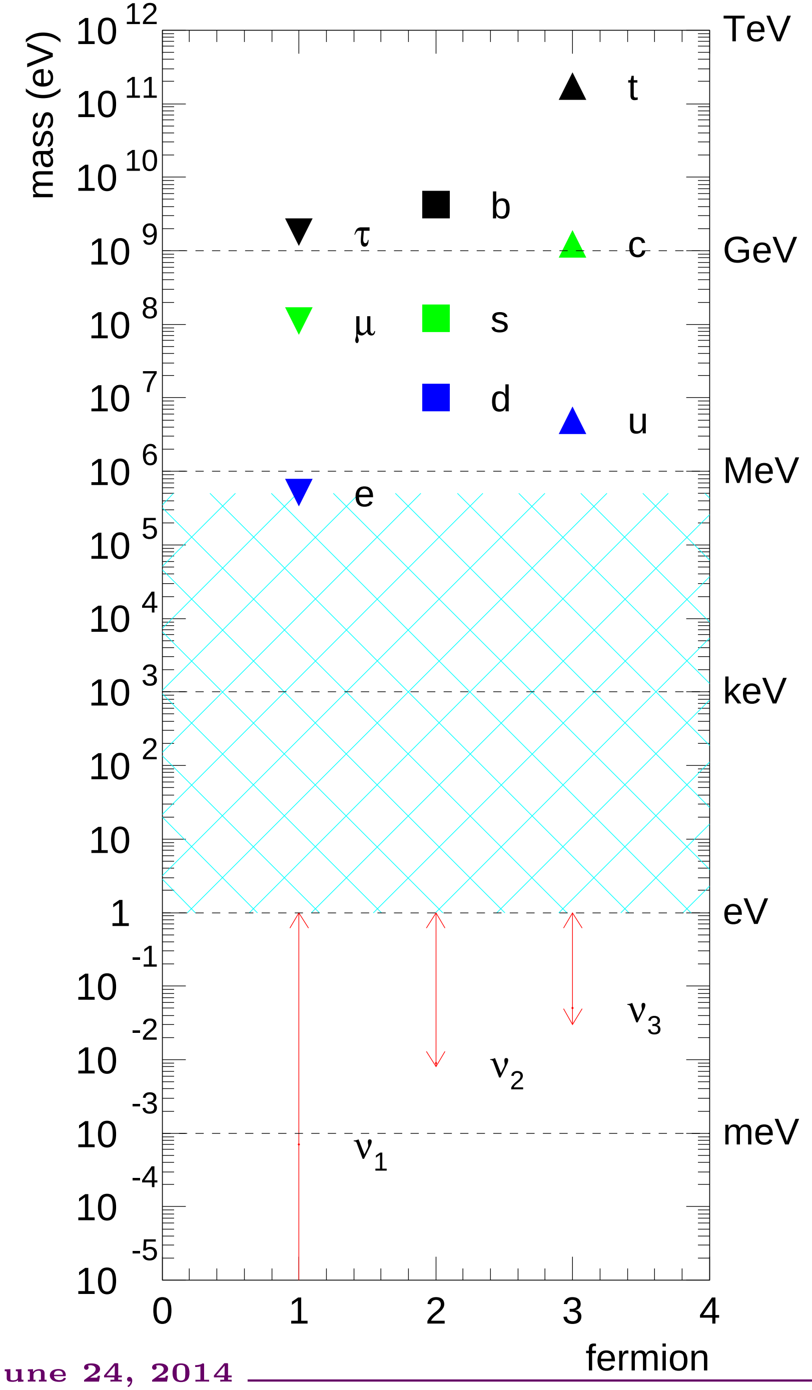
- come in three flavors (see figure);
- interact only via weak interactions;
- have ZERO mass;
- 2 degrees of freedom:
  - left-handed state ν,
  - right-handed state $\bar{\nu}$;
- neutrinos carry lepton number:
  - $L(\nu) = +1$,
  - $L(\bar{\nu}) = -1$.

Over the past decade, the picture changed dramatically. We have discovered that neutrino masses are not zero. In more detail, this is what we discovered:

- Neutrinos Mix.
- Neutrinos Oscillate. This means they can change their flavor after propagating a long distance (depends on the neutrino energy. Oftentimes, it is hundreds of kilometers).

Both of these phenomena occur only if the neutrino masses are not zero, and different from one another.

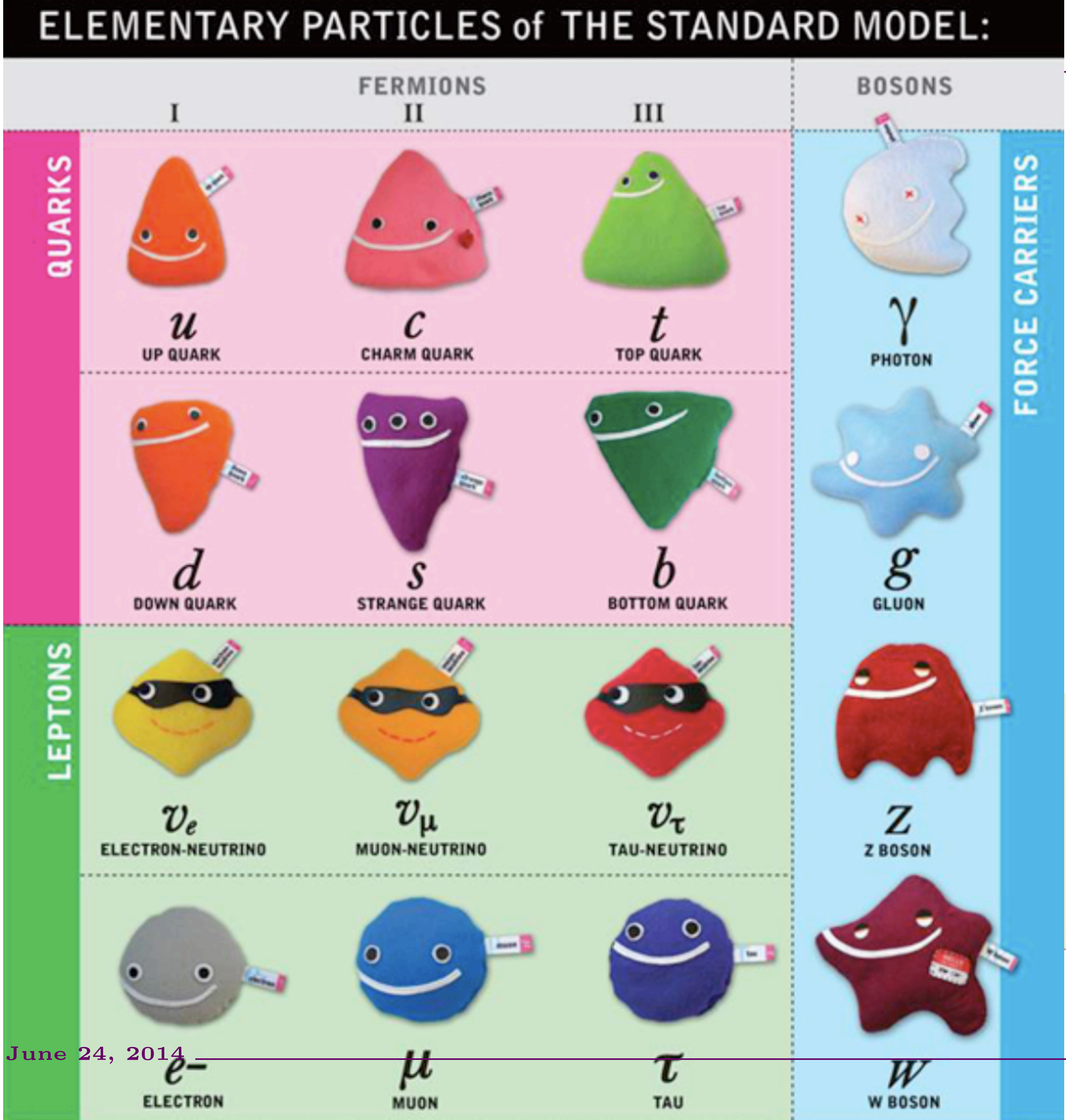
[lecture by Tia Miceli]



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



This is much more than a pretty picture. It is a very powerful, predictive model.

http://www.particlezoo.net

- Result of over 60 years of particle physics theoretical and experimental research.
- Theoretical formalism based on the marriage of Quantum Mechanics and Special Relativity – Relativistic Quantum Field Theory.
- Very Powerful – once we specify the model ingredients: field content (matter particles) and the internal symmetries (interactions), the dynamics of the system is uniquely specified by a finite set of free parameters.

Given the known ingredients of the model and the known rules, we can predict that the neutrino masses are exactly zero.

Neutrino masses require new ingredients or new rules. We are still try to figure out what these new ingredients are.

On the plus side, we probably know what they could be...

Neutrino Masses, Higgs Mechanism, and New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly**;

2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking!;

3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism.

We are going to need a lot of experimental information from all ares of particle physics in order to figure out what is really going on!

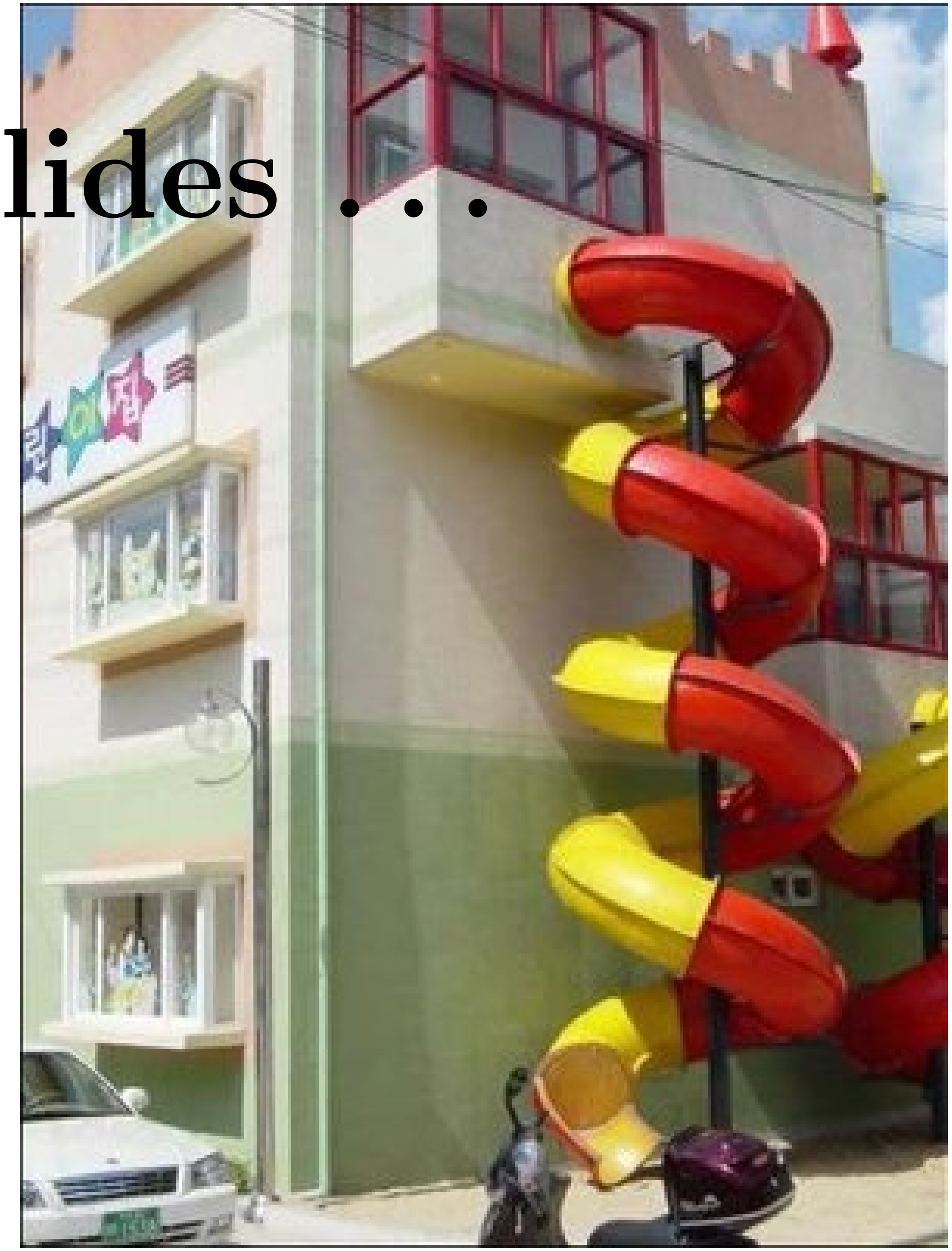
(Some of the) Ongoing Neutrino Physics Activity at FERMILAB

- MINOS;
- MiniBooNE;
- Minerνa;
- NOνA;
- MINOS+;
- MicroBooNE;
- LBNE.

and several other plans for the future!

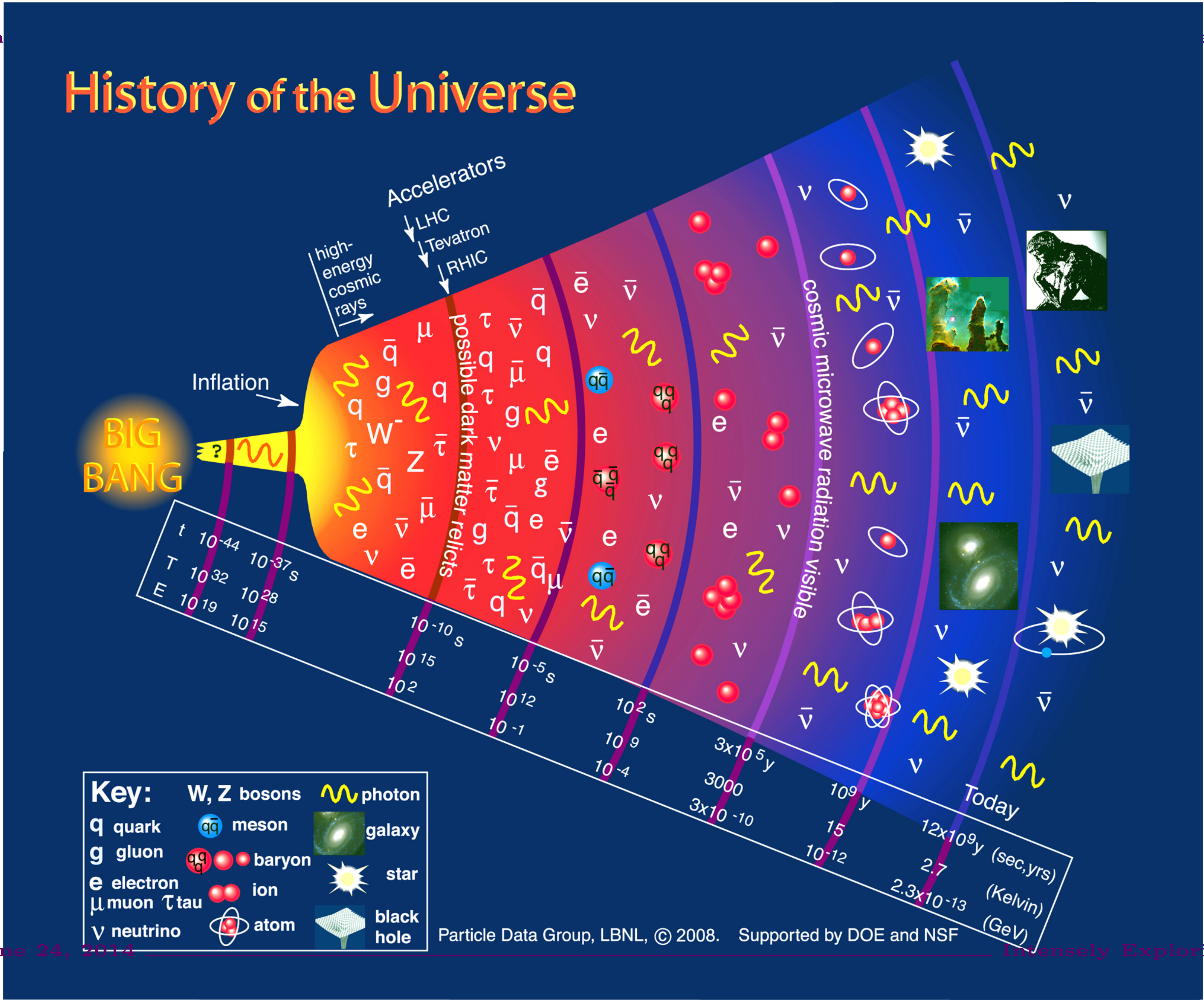
[lecture by Tia Miceli]

Backup Slides . . .



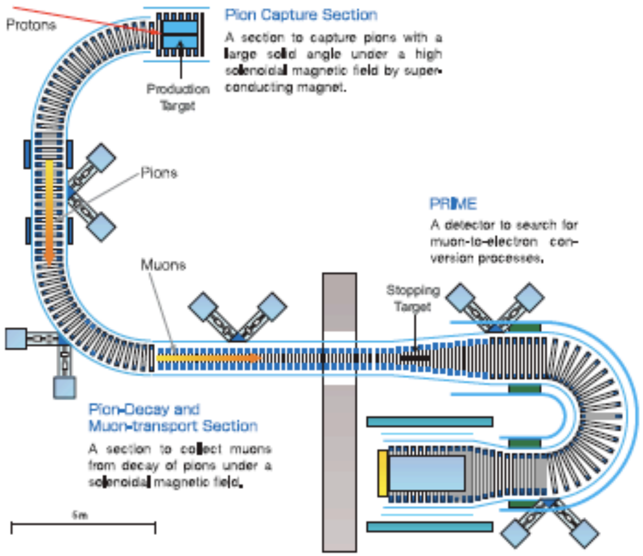
"I have done something very bad today by proposing a particle that cannot be detected; it is something that no theorist should ever do."

- Wolfgang Pauli


History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
µ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Staging Approach to Search for Muon to Electron Conversion

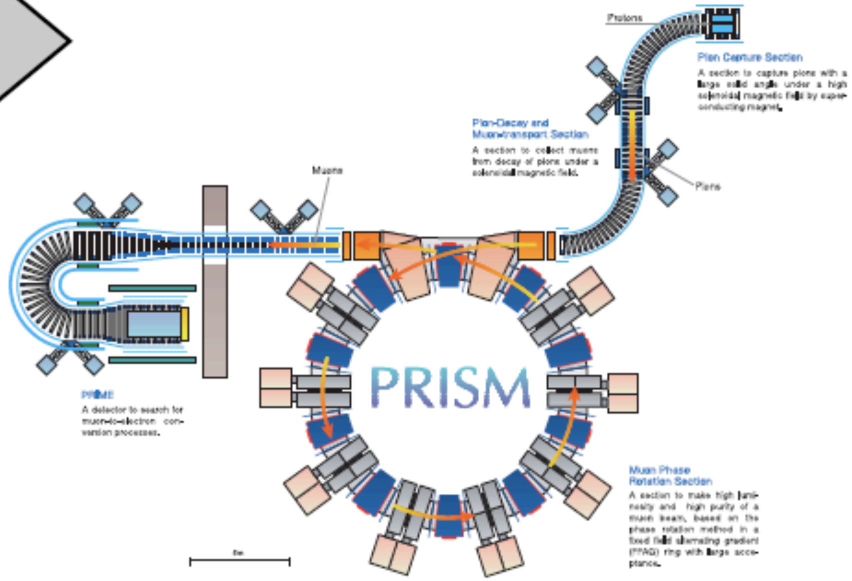
Phase 1 : COMET



$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- use a slowly-extracted pulsed proton beam.
- medium proton beam power (60 kW)
- can be done at the J-PARC NP Hall.
- Early realization

Phase 2 : PRISM



$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- with a muon storage ring.
- use a fast-extracted pulsed proton beam.
- very high beam pwer (>1 MW)
- need a new beamline of fast extraction.
- Ultimate search

What Will Be Happening in the Near Future... (I Hope!)

- MEG: $\mu \to e\gamma$ at several $\times 10^{-14}$.
- $g-2$ measurement a factor of 3–4 more precise.
- COMET (Phase I) $\mu \to e$-conversion at $\times 10^{-14}$.
- Mu2e and COMET (Phase II) $\mu \to e$-conversion at several $\times 10^{-17}$.
- PSI: $\mu \to eee$ at 10^{-15}.
- SuperB: Rare τ processes at 10^{-10}.
- Next-next-generation: $\mu \to e$-conversion at 10^{-18} (or precision studies?).
- Next-next-generation: deeper probe of muon edm.
- Muon Beams/Rings: $\mu \to e$-conversion at 10^{-20}? Revisit rare muon decays ($\mu \to e\gamma$, $\mu \to eee$) with new idea?

(Time permitting. . .)

One last topic: **Proton (Nucleon) Decay**

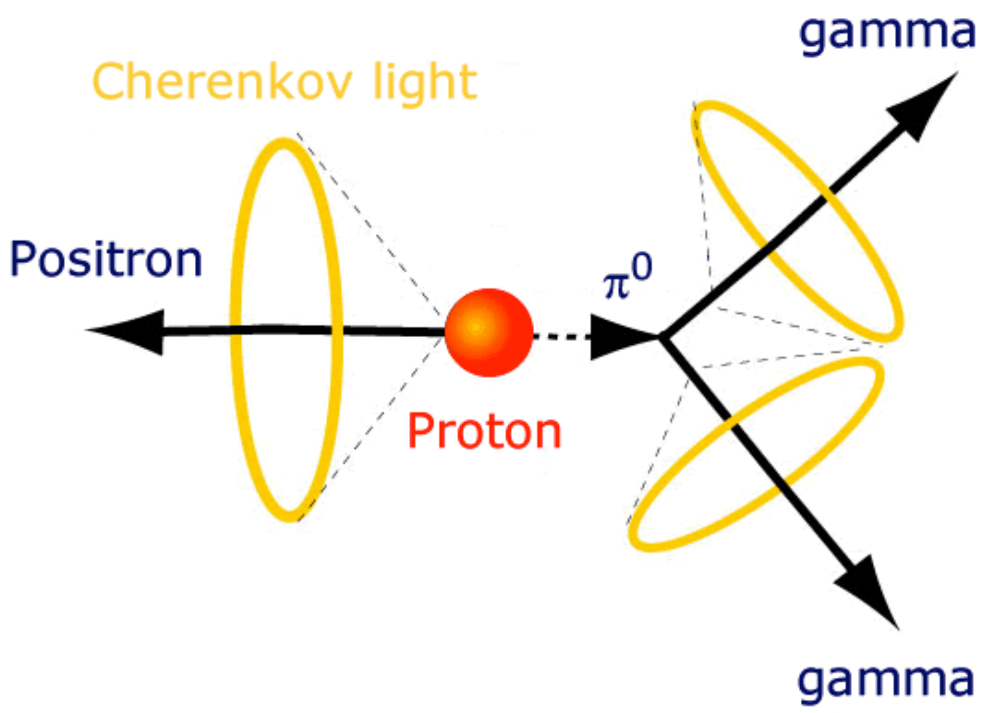
As far as we can tell, ordinary matter – i.e., protons and many complex nuclei (^{4}He, ^{16}O, ^{14}N, ^{56}Fe, etc) – is absolutely stable. Why is that?

The answers is we don't know. In the Standard Model, however there are no interactions that will ever make the proton decay (not totally true, but I will ignore some subtleties).

We understand why that is. The Standard Model has a symmetry – **baryon number**, which renders the lightest baryon – it happens to be the proton – stable. Baryon number is an **accidental symmetry**. We did not ask for it, it happened as a side-effect of the known particles and interactions.

The other stable particles:

- photon – massless!
- lightest neutrino – lightest particle with spin 1/2. Other two?
- electron – lightest particle with nonzero electric charge.
- dark matter – Is it? Why?



Nucleon Decay Limits

antilepton + meson